



LAWRENCE  
LIVERMORE  
NATIONAL  
LABORATORY

# Spectroscopy with trapped highly charged ions

P. Beiersdorfer

January 25, 2008

Physica Scripta

## **Disclaimer**

---

This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

# Spectroscopy with trapped highly charged ions

Peter Beiersdorfer\*

High Temperature and Astrophysics Division, Lawrence Livermore National Laboratory, 7000 East Avenue  
L-260, Livermore, CA 94550, USA

## Abstract

We give an overview of atomic spectroscopy performed on electron beam ion traps at various locations throughout the world. Spectroscopy at these facilities contributes to various areas of science and engineering, including but not limited to basic atomic physics, astrophysics, extreme ultraviolet lithography, and the development of density and temperature diagnostics of fusion plasmas. These contributions are accomplished by generating, for example, spectral surveys, making precise radiative lifetime measurements, accounting for radiative power emitted in a given wavelength band, elucidating isotopic effects, and testing collisional-radiative models. While spectroscopy with electron beam ion traps had originally focused on the x-ray emission from highly charged ions interacting with the electron beam, the operating modes of such devices have expanded to study radiation in almost all wavelength bands from the visible to the hard x-ray region; and at several facilities the ions can be studied even in the absence of an electron beam. Photon emission after charge exchange or laser excitation has been observed, and the work is no longer restricted to highly charged ions. Much of the experimental capabilities are unique to electron beam ion traps, and the work performed with these devices cannot be undertaken elsewhere. However, in other areas the work on electron beam ion traps rivals the spectroscopy performed with conventional ion traps or heavy-ion storage rings. The examples we present highlight many of the capabilities of the existing electron beam ion traps and their contributions to physics.

PACS numbers: 32.30.Jc, 32.30.Rj, 32.10.Fn, 32.60.+i, 32.70.Cs, 32.70.Fw, 34.70.+e, 34.80.-i, 37.10.Gh, 37.10.Ty

---

\*Email address: beiersdorfer@llnl.gov

# 1. Introduction

More than twenty years ago, the first electron beam ion trap, now dubbed EBIT-I, was put into service to study the physics of highly charged ions interacting with a monoenergetic electron beam [1]. The new device, operated at the Lawrence Livermore National Laboratory, was specifically designed for spectroscopy. It provided direct line of sight access to the ions in the trap by using a set of Helmholtz coils to generate the magnetic field without blocking the view of the trapping region. This was an important departure from using a solenoid, which was the method of choice for electron beam ion sources at the time [2]. The device was immediately successful as a spectroscopic light source. Though it was much dimmer than other light sources, such as tokamaks or laser-plasma sources, it made up for it by allowing continuous operation and unsurpassed control over the operating conditions.

Initial experiments with the EBIT-I electron beam ion trap centered on studying the x-ray emission of various ions, notably for x-ray laser research [3]. However, it became quickly apparent that the device could be used for measurements in a variety of wavelength bands [1, 4]. Various novel operating regimes were developed that extended its usefulness to measuring not only transition energies, but also radiative decay rates, electron-impact excitation and ionization cross sections, dielectronic recombination rates, and ionization equilibria under quasi-Maxwellian temperature conditions [1]. The development of the magnetic trapping mode [5, 6, 7], for example, in which the electron beam is turned off, allowed the measurement of spectra produced by charge exchange [8]. In this mode, the electron beam ion trap device operates like a Penning trap, and essentially all classes of experiments performed with such traps are now possible with electron beam ion traps. In parallel, dedicated systems for the interrogation of the ions and the detection of the emitted photons, including lasers, microcalorimeters, and polarimeters, have been developed for use on electron beam ion traps. These extend the capabilities of traditional spectroscopy and allow new experiments with trapped ions.

On one hand, the electron beam ion trap competes in its capabilities and type of research performed with other types of devices for studying trapped ions, notably heavy-ion storage rings [9]. The electron beam ion traps are, however, considerably cheaper to build and operate, and in many ways they are more versatile. Even when studying ions with charge as high as  $\text{U}^{92+}$  or  $\text{Cf}^{96+}$  in an electron beam ion trap, for example, Doppler shifts are not an issue [10]. On the other hand, electron beam ion traps provide data impossible to produce with heavy-ion storage ring facilities and conventional Penning and Kingdon ion traps, and thus provide complementary data. A search of the publication data base of the Digital Library for Physics and Astronomy operated by the Smithsonian Astrophysical Observatory ([http://adsabs.harvard.edu/physics\\_service.html](http://adsabs.harvard.edu/physics_service.html)) covering the years between 2000 and 2006 reveals that storage ring and electron beam ion trap facilities produced about equal amounts of papers in physics and astronomy using trapped highly charged ions, as shown in Fig. 1. Of course, not all of these papers concern spectroscopy.

Given the demonstrated utility of electron beam ion traps, it is not surprising that by now about a dozen such devices have been put into operation throughout the world, and new electron beam ion trap devices are

still being planned. For example, electron beam ion traps are under construction or have recently been put on line at the Harvard-Smithsonian Center for Astrophysics, at the isotope science facility at the Michigan State University, at the Queen’s University in Belfast, and at the AlbaNova Physics Center of the University of Stockholm.

In the following we will give an overview of the physics studied with these devices at various institutions. We point out that atomic spectroscopy of trapped ions is only one of several reasons for operating electron beam ion traps. In fact, several such facilities were built with other purposes in mind, such as to provide ions for collision experiments with extracted ions [11] or as charge breeders for mass measurements of radioactive nuclei [12]. Our focus in the examples we present will be specifically on the spectroscopic research of trapped ions.

## 2. The electron beam ion trap

The physics behind electron beam ion traps has been described in several publications [2, 13]. The principle that distinguishes an electron beam ion trap from electron beam ion sources or other types of traps is the presence of a highly focused (i.e., high current-density) electron beam that ionizes, confines, and traps the ions within a relatively small (few cm) volume, as illustrated in Fig. 2. The ions are longitudinally confined by applying the appropriate voltages to a set of three drift tubes through which the beam passes. Radial confinement is provided by the electrostatic attraction of the electron beam as well as by the axial magnetic field. All three drift-tube voltages float on top of a common potential supplied by a high-voltage power source, and the electron beam energy is determined by the sum of the applied potentials minus the effective space charge of the beam. The electron beam density at a given beam energy can be selected by varying the beam current and the magnetic confinement fields.

Since the EBIT-I device was built in 1986, various changes to the its original design have been made. For example, permanent magnets, which significantly reduce cost, have been substituted in the Dresden devices for the original 3 T superconducting magnetic in EBIT-I [14]; by contrast, the electron beam ion trap at Heidelberg (formerly at the University of Freiburg) uses an 8 T superconducting magnet [15], which allows it to accommodate higher electron beam currents. In addition, both higher and lower energy devices have been built. In fact, the various electron beam ion traps that have come on line during the past decade differ substantially from each other. To illustrate this point, we show in Fig. 3 schematics of three recently developed electron beam ion trap devices. The differences in the design are quite dramatic. As a consequence, there are significant differences in performance. These extend from the more obvious performance characteristics, such as the maximum charge state achievable, to more subtle performance characteristics, such as how smeared out a given charge balance may be, the level of neutral background gases, the presence of contaminants, or the degree of control over the electron beam energy and the length of time to achieve ionization equilibrium. Differences also arise from how the trap is filled – with neutral gases, laser ablation [16], wire-probes [17], low-charge ions from arcs or laser sources [18, 19], or ions from radioactive beams [12].

Important for this review is the type of spectroscopic instrumentation in use at the various facilities. While solid-state detectors are ubiquitous, because they provide real-time information on the x-ray production in

the device and thus feedback on device performance as operating parameters are tuned, other spectroscopic instrumentation is rather unique to a given facility. The spectroscopic instrumentation at Livermore is probably the most extensive of any facility. It includes a dozen different crystal spectrometers spanning all geometries from flat-crystal spectrometers for broad-band survey and very high-resolution measurements [20, 21, 22, 23] to cylindrically bent crystal spectrometers in the von Hámos, Johann, and Cauchois geometries [24, 25, 26, 27] and spherically bent crystal spectrometers for x-ray line polarization measurements [28]. It also includes multiple grating spectrometers for studying the emission in the EUV, UV, and optical wavelength bands [29, 30, 31, 32, 33] and various filter and prism-based optical spectrometers [34, 35, 36]. High-resolution microcalorimeters at the Livermore electron beam ion trap facility are now in their fourth generation, starting from a single-pixel device [37, 38] that has later been used at the electron beam ion trap facility at the National Institute of Standards and Technology (NIST) in Gaithersburg [39], to various 36-pixel arrays developed at the Goddard Space Flight Center [40], which now provide excellent energy resolution even when measuring hard x rays and gamma rays up to 60 keV [41, 42]. Figure 4 shows the EBIT Calorimeter Spectrometer (ECS) microcalorimeter [43] and the high-resolution EUV grating spectrometer [33] on the SuperEBIT high-energy electron beam ion trap at Livermore.

Several electron beam ion trap facilities throughout the world are specifically dedicated to the spectroscopy of highly charged ions. These include the EBIT-I and SuperEBIT devices at Livermore, where essentially all research is conducted *in situ* by viewing the radiation from the ions in the trap [44]. Others are hybrid facilities, which are not only used for *in situ* spectroscopy, but are also used as ion sources. These include, for example, the facility at Berlin [45] and Tokyo [46]. Here the ions are bred in the trap and then extracted for performing a variety of research, which may include ion-surface interactions or charge-exchange studies. The electron beam ion trap device at Gaithersburg was in that group, but has recently changed its focus to pure *in situ* spectroscopy [47]. Several electron beam ion trap facilities are essentially exclusively used as ion sources, such as the EBIT-II device [48] after it was moved from Livermore to the Lawrence Berkeley Laboratory, or as charge breeders for nuclear mass measurements developed at TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) on-line facility [49].

### 3. Spectroscopy on electron beam ion traps

In the following, we give brief highlights of work performed *in situ* using spectroscopy. By its nature, this overview will be incomplete, but we hope to touch upon the major aspects of work performed at each institution since the respective machine came into operation.

#### 3.1 New facilities: Stockholm, Shanghai

The electron beam ion trap devices at Fudan University in Shanghai and at the AlbaNova Physics Center of the University of Stockholm are probably the most recent facilities to generate spectroscopic data [50, 51]. Both facilities have performed measurements of the KLL dielectronic resonances using a solid-state detector, as illustrated in Figs. 5 and 6.

The plot from Stockholm shows the x rays from near-heliumlike silicon ions produced by radiative recombination (RR) and dielectronic recombination (discrete islands) as the electron beam energy was scanned. It also shows the x rays produced by direct electron-impact excitation (lines at fixed x-ray energy) as the threshold energy for this process is crossed. The plot from Shanghai shows the x rays from near-heliumlike xenon ions produced by dielectronic recombination (discrete islands) as the electron beam energy was swept over the KLL resonances [52, 53].

### 3.2 Dresden

The effort at Dresden has focused mainly on the development of cryogen-free, compact electron beam ion traps, and several models have been built so far. These devices utilize warm permanent magnets to compress the electron beam. They are thus unique among the existing devices. Another distinguishing feature has been the intensive use of organo-metallic compounds to fill the trap with metal ions via gas injection [54].

While x-ray scatter plots similar to those shown in Figs. 5 and 6 have been reported by the Dresden group, they have also used a flat-crystal spectrometer to record the x-ray emission [55]. The spectrum of neonlike xenon resulting from such a measurement is shown in Fig. 7.

### 3.3 Oxford

The electron beam ion trap at the University of Oxford, England, together with the one at NIST were the first to be built outside Livermore [56]. Both were built at Oxford using a slightly modified Livermore design.

The Oxford electron beam ion trap has been used for high-resolution spectroscopy. Significant atomic physics results have been achieved, notably in testing predictions of quantum electrodynamics (QED) and performing accurate transition energy measurements [57, 58, 59].

This facility was the first to successfully employ a laser to probe trapped ions. Using a CO<sub>2</sub> laser the Oxford group measured the  $2s_{1/2}$ - $2p_{3/2}$  energy in N<sup>6+</sup> to determine the Lamb shift contribution. The transition energy was measured to be  $835.0 \pm 0.5 \text{ cm}^{-1}$ , in agreement with QED theory [60]. The setup employed in this measurement and the resonance probed with the laser are shown in Fig. 8.

### 3.4 Tokyo

The Tokyo electron beam ion trap at the University of Electro-Communications, in Chofu, Japan is the first high-energy electron beam ion trap built outside Livermore [61]. The machine has been equipped to be an ion source. Experiments with extracted ions have yielded important atomic physics results, including cross section studies of dielectronic recombination and x-ray yields from ion-surface interactions [62, 63].

The Tokyo electron beam ion trap has been an important source of spectroscopic data for basic atomic physics. In addition to dielectronic resonance data obtained with solid-state detectors, as illustrated in Fig. 9, multiple studies involving high-resolution spectroscopy have been performed. For example, a crystal spectrometer provided systematic energy level data on neonlike ions with atomic number  $Z$  in the mid 50s [64, 65]. By filling in data along the iso-electronic sequence of earlier measurements on tokamaks [66, 67], the physics of avoided level crossings was elucidated, as shown in Fig. 10.

Crystal spectroscopy at the Tokyo electron beam ion trap also included a measurement of the K-shell emission of heliumlike  $\text{In}^{47+}$  [68], which is the highest- $Z$  heliumlike ion (and the shortest wavelength) observed by a reflection-type crystal spectrometer on an electron beam ion trap. By contrast, the spectrum of heliumlike  $\text{Xe}^{52+}$  was studied on SuperEBIT using a transmission-type crystal spectrometer [69]. Another example of a hard x-ray measurement – possibly not noted by the community – is the determination of the 1s binding energy of hydrogenlike rhodium [70]. This allowed a test of the 1s Lamb shift at the 3.4 eV level.

X-ray line polarization studies on EBIT-I and EBIT-II at Livermore [71, 72, 73] and at the electron beam ion trap at Gaithersburg [74] of transitions in heliumlike and neonlike ions had found rather good agreement with modern relativistic theory. Reasonable agreement had also been obtained at relativistic electron energies as high as 120 keV [75]. A crystal spectrometer measurement at the Tokyo electron beam ion trap was the first to indicate significant differences with theory. The measurement involved the Lyman- $\alpha$  lines of hydrogenlike  $\text{Ti}^{21+}$  [76] and had been carried out to energies as high as 50 keV (or ten threshold units). The results spurred measurements of the Lyman- $\alpha$  lines of  $\text{Ar}^{17+}$  and  $\text{Fe}^{25+}$  on SuperEBIT with electron energies as high as 25 threshold units [77]. The results, shown in Fig. 11, are overall well below theory and appear to confirm that there are unresolved issues for such a simple atomic system.

### 3.5 Berlin

The electron beam ion trap in Berlin follows the Livermore design for EBIT-II [78]. Most of its focus has been on atomic data for magnetic fusion using a variety of spectroscopic equipment.

A measurement of the excitation function of krypton obtained with a solid-state detector is shown in Fig. 12(a). Unlike similar measurements at other facilities where the observed emission simply reflects the ionization balance prevalent at the time of the measurement, the ionization balance for the Berlin measurement was specifically chosen to be that predicted for a plasma temperature of 4.7 keV [79]. Under this condition one can use the observed photon emission as a function of beam energy to derive the radiative cooling rate at this temperature by folding the observed emission with the appropriate weight function (shown in Fig. 12(b)). The resulting cooling rate is shown in Fig. 12(c), where it is compared to various theoretical predictions.

The Berlin machine is equipped with a versatile EUV spectrograph. Two measurement examples are shown in Figs. 13 and 14. The spectrum in Fig. 13 shows the emission of various tungsten ions in the far ultraviolet [80]. This wavelength region has received little attention so far, but is important for impurity monitoring of magnetic fusion plasmas, especially in light of the planned ITER magnetic fusion test reactor [81, 82], which may employ tungsten armor in regions that need to withstand a high heat flux. The spectrum in Fig. 14 shows the emission of various xenon ions in the extreme ultraviolet [83]. Xenon has been proposed as a coolant to reduce the heat load on the armor plates in future magnetic fusion devices. In both cases the beam energy was stepped through various ionization thresholds in order to aid the line identification.



### 3.6 Gaithersburg

The electron beam ion trap at NIST in Gaithersburg, is the first such device to operate outside Livermore [84]. The NIST electron beam ion trap group was the first to report detailed measurements of transitions in highly charged ions in the visible. The particular line studied was the  $3d^4\ ^2D_{3/2} - 3d^4\ ^2D_{5/2}$  transition from titaniumlike  $\text{Xe}^{32+}$  and  $\text{Ba}^{34+}$  [85]. Unlike other fine structure transitions, this particular transition remains in the visible even as  $Z$  increases. For bismuth, its wavelength is still well above 3400 Å, i.e., it is still in the optical regime. The reported wavelengths were in poor agreement with theory, spurring more experimental and theoretical investigations. Measurements subsequently performed at NIST [86], Tokyo [87], and Livermore’s EBIT-II device [88] are shown in Fig. 15 and compared to improved theory [89].

Line identifications in the optical regime are often complicated by the fact that theoretical predications may differ by tens of Ångströms and more. Such differences exist not only in complex, multi-electron ions, such as the just mentioned titaniumlike system, but even hydrogenlike systems can differ by such amounts from theory [90, 91]. Identification is greatly helped by the ability to vary the electron beam energy and to see lines appear as the ionization threshold to make the next higher charge state is crossed, as illustrated earlier for lines in the ultraviolet (cf. Figs. 13 and 14). This method was used at Gaithersburg to track from 100 eV to 10 keV the intensity and position of a visible line of xenon of interest in EUV lithography [92]. It was concluded that the line, shown in Fig. 16, is from  $\text{Xe}^{9+}$  with a wavelength of  $5983.0 \pm 1.3$  Å. This result was said to correct an earlier measurement at Livermore, which claimed that a line near 5984 Å arose from  $\text{Xe}^{31+}$  [93]. It was stated that “We have found no evidence to support the claim by others that a line near this position originates from  $\text{Xe}^{31+}$ ” [92]. This statement was surprising, because the Livermore assignment was also based on varying the beam energy: the line appeared at a beam energy around 1870 eV, i.e., when the threshold for producing  $\text{Xe}^{31+}$  ions was crossed, and vanished below that energy. This puzzle was resolved in a measurement at the Berlin electron beam ion trap (cf. Fig. 17). The group at Berlin found that at low energy there is a line at  $5980.4 \pm 0.3$  Å from  $\text{Xe}^{9+}$  and that at higher energies there is a line at  $5982.1 \pm 0.3$  Å from  $\text{Xe}^{31+}$  [94].

The above example illustrates that line identification cannot always rely on merely scanning the electron beam energy. This method works only, if the charge distribution in the machine is narrowly peaked. A broad charge state distribution had been reported earlier from the Gaithersburg electron beam ion trap in the case of  $\text{Fe}^{16+}$ . From simple charge balance calculations this ion stage is expected to burn out around 1500 eV [95]. This expectation was confirmed in measurements on EBIT-II at Livermore [96]. Using a single-pixel microcalorimeter the Fe XVII x-ray emission was detected, however, at the Gaithersburg electron beam ion trap at beam energies of 4000 eV and beyond [97].

Effects related to a broad ionization balance may have affected the Gaithersburg measurement of the Fe XVII line intensities [98], which was subsequently determined to be erroneous [99, 100]. By contrast, a recent measurement at the Gaithersburg electron beam ion trap of Ni XIX [101], which is in the same isoelectronic sequence as Fe XVII, was found to agree well with the earlier Livermore data [102, 103, 104].

### 3.7 Heidelberg

The electron beam trap at the Max Planck Institute for Nuclear Physics in Heidelberg was first operated at the University of Freiburg before its move to Heidelberg [15]. Several new machines have been built at Heidelberg since, including the one now operating at TRIUMF and another one used at the free-electron laser at the synchrotron facility in Hamburg [12, 105].

The Heidelberg electron beam ion trap has been used intensively to study the ground state fine structure transition in boronlike  $\text{Ar}^{13+}$ . The wavelength of this transition was measured with extremely high accuracy,  $4412.559 \pm 0.001 \text{ \AA}$  [106], as illustrated in Fig. 18. The accuracy of the measurement exceeds that of the best calculations by a factor of 3000. These calculations suggest that the line's wavelength is shifted by  $9.6 \text{ \AA}$  due to QED.

In a subsequent measurement even higher precision was achieved by utilizing evaporative cooling [107, 108] to reduce the Doppler motion of the ions in the trap. At ion temperatures as low as 6 eV, the six Zeeman components became readily apparent, as illustrated in Fig. 19 [109]. Observation of the splitting is aided by the fact that the Heidelberg electron beam ion trap is operated at a field strength of 8 T, which is almost three times higher than that of the Livermore, Berlin, or Gaithersburg machines and 10–20 times higher than that of the Dresden machines. By studying the boronlike fine structure transition both in  $^{36}\text{Ar}^{13+}$  and  $^{40}\text{Ar}^{13+}$  an isotope shift of  $0.0123 \pm 0.0006 \text{ \AA}$  was determined, which perfectly agreed with predictions [109].

Employing the magnetic mode of operation [6], the Heidelberg electron beam ion trap has also been used to measure the radiative rate of the  $\text{Ar}^{13+} \ ^2P_{1/2} - ^2P_{3/2}$  ground state fine structure transition [110]. The Heidelberg measurement of  $9.573 \pm 0.004 \pm 0.005 \text{ ms}$  (stat/syst) for the corresponding radiative lifetime achieved a precision that exceeded that of previous measurements by more than an order of magnitude. Interestingly, only one of the previous three measurements of this transition agreed within error bars with the Heidelberg result, although all measurements were performed using ions traps. The result in agreement with the Heidelberg measurement is the  $9.70 \pm 0.15 \text{ ms}$  measurement performed at Livermore [111]. The  $9.12 \pm 0.18 \text{ ms}$  result from a measurement using a Kingdon trap is too short [112]; even shorter is the  $8.7 \pm 0.5 \text{ ms}$  result obtained at the Gaithersburg electron beam ion trap [113].

The high accuracy of the Heidelberg radiative lifetime measurement makes it sensitive to the electron anomalous magnetic moment  $g - 2$ . Surprisingly, the calculations thought to be the most accurate and that include the contribution from the electron anomalous magnetic moment differ from the measured value by three  $\sigma$ , while those that do not include the effect are in agreement. This is illustrated in Fig. 20.

A subsequent measurement performed at the Heidelberg electron beam ion trap centered on the  $^{26}\text{Fe}^{13+} \ ^2P_{1/2} - ^2P_{3/2}$  ground state fine structure transition of aluminumlike  $\text{Fe}^{13+}$  [114] confirmed the conclusions of the  $\text{Ar}^{13+}$  measurement. The highly accurate result of  $16.726^{+0.020}_{-0.010} \text{ ms}$  is again in agreement with the earlier Livermore result of  $16.74 \pm 0.12 \text{ ms}$  [115], but it is shorter than the  $17.0 \pm 0.2 \text{ ms}$  and  $17.52 \pm 0.29 \text{ ms}$  results obtained on Kingdon traps [116, 117]. It is also shorter than the  $18.0 \pm 1.2 \text{ ms}$  result obtained at the TSR heavy-ion storage ring at Heidelberg [118]. As noted before for argon, inclusion of the contribution from the electron anomalous magnetic moment destroys agreement with the measured value.

### 3.8 Livermore

As mentioned earlier, the Livermore electron beam ion traps are the oldest of their kind, and spectroscopic measurements on the SuperEBIT and EBIT-I facility remaining in Livermore have spanned the areas now found at the other electron beam ion trap facilities as well as areas not pursued elsewhere, including measurements in support of magnetic fusion [119], high energy density physics [120, 121, 122], astrophysics [123, 124, 125], and basic atomic physics such as highly accurate QED determinations and measurements of electron-impact excitation cross sections [126, 127, 128]. In the following we give examples only of recent radiative lifetime measurements. Unlike the measurements already mentioned, the following measurements have been carried out by studying x-ray transitions.

The possibility of radiative lifetime measurements using an electron beam ion trap has been demonstrated first at Livermore in a determination of the 91  $\mu\text{s}$  lifetime of the  $1s2s\ ^3S_1$  excited level of heliumlike  $\text{Ne}^{8+}$  [129]. Since then measurements of heliumlike ions at Livermore have explored five orders of magnitude, from tens of milliseconds to hundreds of nanoseconds [130], as illustrated in Fig. 21. This figure also shows that electron beam ion traps occupy a specific niche for such measurements, in which no other facility currently can perform measurements. This niche is bounded on one end by heavy-ion storage rings and externally filled ion traps and on the other end by beam-foil and slow recoil ion spectroscopy.

Another example is the measurement of the radiative lifetime of the  $3d_{5/2}^9 4s_{1/2}\ ^3D_3$  level. This level is the lowest-excited level in the nickellike isoelectronic sequence. It can decay to the  $3d^{10}\ ^1S_0$  ground state only via a magnetic octupole transition, as first observed at Livermore in 1991 [131] and recently rediscovered at the Gaithersburg electron beam ion trap [132]. The radiative rate of the magnetic octupole transition was first measured using the second-generation Goddard microcalorimeter on EBIT-I for  $\text{Xe}^{26+}$ ,  $\text{Cs}^{27+}$ , and  $\text{Ba}^{28+}$  [133]. The microcalorimeter measurement studied elements with naturally abundant isotope ratios. Odd-nucleon isotopes have a non-zero nuclear magnetic moment, which leads to hyperfine-induced mixing of the  $^3D_3$  level with the neighboring  $^3D_2$  level. This level decays via an electric quadrupole transition [134] and at a rate orders of magnitude faster than the rate associated with the magnetic quadrupole decay. Measurements on SuperEBIT with isotopically pure  $\text{Xe}^{26+}$  ions have verified this mixing [135], as illustrated in Fig. 22, which in  $^{129}\text{Xe}^{26+}$  shortens the  $^3D_3$  lifetime by almost a factor of six.

## 4. Conclusion

Hopefully this brief overview has successfully illustrated the current vitality of atomic physics studies with electron beam ion traps. Electron beam ion traps occupy a niche that cannot (yet) be touched by other kinds of facilities, including standard ion traps and storage rings. In other areas, electron beam ion traps are highly competitive with these facilities.

Spectroscopy of highly charged ions is not yet a complete field, and new discoveries continue to be made. In addition, there is a great need for spectroscopic data throughout physics, such as astrophysics, high-energy density physics, and fusion research. As a result, electron beam ion traps will continue to be an important platform for generating atomic data and advancing modern physics.

## **Acknowledgements**

This work was performed by the Lawrence Livermore National Laboratory under the auspices of the Department of Energy under under Contract DE-AC52-07NA27344.

## References

- [1] P. Beiersdorfer, Can. J. Phys. **86**, in press (2008).
- [2] R. E. Marrs, Can. J. Phys. **86**, in press (2008).
- [3] J. Nilsen, Can. J. Phys. **86**, in press (2008).
- [4] P. Beiersdorfer, J. A. Britten, G. V. Brown, H. Chen, E. J. Clothiaux, J. Cottam, E. Förster, M.-F. Gu, C. L. Harris, S. M. Kahn, J. K. Lepson, P. A. Neill, D. W. Savin, H. Schulte-Schrepping, L. Schweikhard, A. J. Smith, E. Träbert, J. Tschischgale, S. B. Utter, and K. L. Wong, Phys. Scripta **T92**, 268 (2001).
- [5] P. Beiersdorfer, B. Beck, R. E. Marrs, S. R. Elliott, and L. Schweikhard, Rapid Commun. Mass Spectrom. **8**, 141 (1994).
- [6] P. Beiersdorfer, L. Schweikhard, J. Crespo López-Urrutia, and K. Widmann, Rev. Sci. Instrum. **67**, 3818 (1996).
- [7] P. Beiersdorfer, B. Beck, S. Becker, and L. Schweikhard, Int. J. Mass Spectrom. Ion Proc. **158**, 149 (1996).
- [8] P. Beiersdorfer, K. R. Boyce, G. V. Brown, H. Chen, S. M. Kahn, R. L. Kelley, M. May, R. E. Olson, F. S. Porter, C. K. Stahle, and W. A. Tilletson, Science **300**, 1558 (2003).
- [9] R. E. Marrs, Comments At. Mol. Phys. **27**, 57 (1991).
- [10] P. Beiersdorfer, S. R. Elliott, J. Crespo López-Urrutia, and K. Widmann, Nucl. Phys. **A626**, C357 (1997).
- [11] G. Zschornack, F. Großmann, R. Heller, U. Kentsch, M. Kreller, S. Landgraf, V. P. Ovsyannikov, M. Schmidt, and F. Ullmann, Nucl. Instrum. Methods Phys. Res. B **258**, 205 (2007).
- [12] G. Sikler, J. R. Crespo López-Urrutia, J. Dilling, S. Epp, C. J. Osborne, and J. Ullrich, Eur. J. Phys. **25**, 63 (2005).
- [13] M. A. Levine, R. E. Marrs, J. N. Bardsley, P. Beiersdorfer, C. L. Bennett, M. H. Chen, T. Cowan, D. Dietrich, J. R. Henderson, D. A. Knapp, A. Osterheld, B. M. Penetrante, M. B. Schneider, and J. H. Scofield, Nucl. Instrum. Methods **B43**, 431 (1989).
- [14] G. Zschornack, R. Heller, M. Kreller, S. Landgraf, F. Großmann, U. Kentsch, V. P. Ovsyannikov, M. Schmidt, and F. Ullmann, Rev. Sci. Instrum. **77**, 03 (2006).
- [15] J. R. Crespo López-Urrutia, B. Bapat, I. Draganic, A. Werdich, and J. Ullrich, Phys. Scripta **T92**, 110 (2001).
- [16] A. M. Niles, E. W. Magee, D. B. Thorn, G. V. Brown, H. Chen, and P. Beiersdorfer, Rev. Sci. Instrum. **77**, 10F106 (2006).

- [17] S. R. Elliott and R. E. Marrs, Nucl. Instrum. Methods **B100**, 529 (1995).
- [18] I. G. Brown, J. E. Galvin, R. A. MacGill, and R. T. Wright, Appl. Phys. Lett. **49**, 1019 (1986).
- [19] M. Trinczek, A. Werdich, V. Mironov, P. Guo, A. J. González Martínez, J. Braun, J. R. Crespo López-Urrutia, and J. Ullrich, Nucl. Instrum. Methods Phys. Res. B **251**, 289 (2006).
- [20] P. Beiersdorfer and B. J. Wargelin, Rev. Sci. Instrum. **65**, 13 (1994).
- [21] G. V. Brown, P. Beiersdorfer, and K. Widmann, Rev. Sci. Instrum. **70**, 280 (1999).
- [22] D. Klöpfel, G. Hölzer, E. Förster, and P. Beiersdörfer, Rev. Sci. Instrum. **68**, 3669 (1997).
- [23] P. Beiersdorfer, J. R. Crespo-López Urrutia, E. Förster, J. Mahiri, and K. Widmann, Rev. Sci. Instrum. **68**, 1077 (1997).
- [24] P. Beiersdorfer, R. E. Marrs, J. R. Henderson, D. A. Knapp, M. A. Levine, D. B. Platt, M. B. Schneider, D. A. Vogel, and K. L. Wong, Rev. Sci. Instrum. **61**, 2338 (1990).
- [25] P. Beiersdorfer, in *AIP Conference Proceedings 389, X-Ray and Innershell Processes*, AIP, edited by R. L. Johnson, H. Schmidt-Böcking, and B. F. Sonntag (AIP, Woodbury, NY, 1997), p. 121.
- [26] K. Widmann, P. Beiersdorfer, G. V. Brown, J. R. Crespo López-Urrutia, V. Decaux, and D. W. Savin, Rev. Sci. Instrum. **68**, 1087 (1997).
- [27] P. Beiersdorfer, J. Crespo López-Urrutia, V. Decaux, K. Widmann, and P. Neill, Rev. Sci. Instrum. **68**, 1073 (1997).
- [28] D. L. Robbins, H. Chen, P. Beiersdorfer, A. Y. Faenov, T. A. Pikuz, M. J. May, J. Dunn, and A. J. Smith, Rev. Sci. Instrum. **75**, 3717 (2004).
- [29] P. Beiersdorfer, J. R. Crespo López-Urrutia, P. Springer, S. B. Utter, and K. L. Wong, Rev. Sci. Instrum. **70**, 276 (1999).
- [30] S. B. Utter, G. V. Brown, P. Beiersdorfer, E. J. Clothiaux, and N. K. Podder, Rev. Sci. Instrum. **70**, 284 (1999).
- [31] S. B. Utter, P. Beiersdorfer, J. R. Crespo López-Urrutia, and E. Träbert, Rev. Sci. Instrum. **70**, 288 (1999).
- [32] S. B. Utter, J. R. Crespo López-Urrutia, P. Beiersdorfer, and E. Träbert, Rev. Sci. Instrum. **73**, 3737 (2002).
- [33] P. Beiersdorfer, E. W. Magee, E. Träbert, H. Chen, J. K. Lepson, M.-F. Gu, and M. Schmidt, Rev. Sci. Instrum. **75**, 3723 (2004).
- [34] H. Chen, P. Beiersdorfer, C. L. Harris, E. Träbert, S. B. Utter, and K. L. Wong, Phys. Scripta **T92**, 284 (2001).

- [35] H. Chen, P. Beiersdorfer, C. L. Harris, S. B. Utter, and K. L. Wong, *Rev. Sci. Instrum.* **72**, 983 (2001).
- [36] E. Träbert and P. Beiersdorfer, *Rev. Sci. Instrum.* **74**, 2127 (2003).
- [37] M. Le Gros, E. Silver, P. Beiersdorfer, J. C. López-Urrutia, K. Widmann, and S. M. Kahn, in *Electron Beam Ion Trap Annual Report 1995*, University of California Lawrence Livermore National Laboratory Report UCRL-ID-124429 (Livermore, CA), p.22 (1996).
- [38] P. Beiersdorfer, H. Chen, K. R. Boyce, G. V. Brown, R. L. Kelley, F. S. Porter, C. K. Stahle, J. K. Lepson, J. G. Jernigan, B. J. Wargelin, and S. M. Kahn, in *In Highlights of Astronomy*, Vol. 13, as presented at the XXVth General Assembly of the IAU - 2003, ed. by O. Engvold (Astronomical Society of the Pacific, San Francisco, California, 2005), p. 633–639 (2005).
- [39] E. Silver, H. Schopper, S. Bandler, N. Brickhouse, S. Murray, M. Barbera, E. Takacs, J. D. Gillaspay, J. V. Porto, I. Kink, J. M. Laming, N. Madden, D. Landis, J. Beeman, and E. E. Haller, *Astrophys. J.* **541**, 495 (2000).
- [40] F. S. Porter, P. Beiersdorfer, K. Boyce, G. V. Brown, H. Chen, J. Gygax, S. M. Kahn, R. Kelley, C. A. Kilbourne, E. Magee, and D. B. Thorn, *Can. J. Phys.* **86**, in press (2008).
- [41] B. R. Beck, J. A. Becker, P. Beiersdorfer, G. V. Brown, K. J. Moody, J. B. Wilhelmy, F. S. Porter, C. A. Kilbourne, and R. L. Kelley, *Phys. Rev. Lett.* **98**, 142501 (2007).
- [42] D. B. Thorn, G. V. Brown, J. H. T. Clementson, H. Chen, M. H. Chen, P. Beiersdorfer, K. R. Boyce, C. A. Kilbourne, F. S. Porter, and R. L. Kelley, *Can. J. Phys.* **86**, in press (2008).
- [43] F. S. Porter, P. Beiersdorfer, G. V. Brown, W. Doriese, R. L. Kelley, C. A. Kilbourne, J. King, K. Irwin, C. Reintsema, and J. Ullom, *J. Low Temp. Phys.* in press (2008).
- [44] P. Beiersdorfer, *Phys. Scripta* **T120**, 40 (2005).
- [45] F. I. Allen, C. Biedermann, R. Radtke, and G. Fussmann, *J. Phys. Conf. Ser.* **58**, 188 (2007).
- [46] H. Watanabe, H. Tobiya, A. P. Kavanagh, Y. M. Li, N. Nakamura, H. A. Sakaue, F. J. Currell, and S. Ohtani, *Phys. Rev. A* **75**, 012702 (2007).
- [47] J. Reader, private communication (2007).
- [48] T. Schenkel, A. Persaud, A. Krämer, J. W. McDonald, J. P. H. nd A. V. Hamza, and D. H. Schneider, *Rev. Sci. Instrum.* **73**, 663 (2002).
- [49] M. Froese, C. Champagne, J. R. Crespo López-Urrutia, S. Epp, G. Gwinner, A. Lapierre, J. Pfister, G. Sikler, J. Ullrich, and J. Dilling, *Hyperfine Int.* **173**, 85 (2006).
- [50] X. Zhu, Y. Liu, X. Wang, Y. Liu, P. Guo, D. Lu, X. Zhang, W. Hu, M. He, L. Liljeby, and Y. Zou, *Nucl. Instrum. Methods Phys. Res. B* **235**, 509 (2005).

- [51] S. Böhm, A. Enulescu, T. Fritiojj, I. Orban, S. Tashenov, and R. Schuch, *J. Phys. Conf. Ser.* **58**, 303 (2007).
- [52] W. D. Chen, W. Hu, Y. Q. Fu, J. Xiao, Y. Liu, F. C. Meng, T. M. Shen, C. Y. Chen, S. Wu, B. Wei, R. Hutton, and Y. Zou, *Phys. Plasma* **14**, 103302 (2007).
- [53] W. Hu, Y. Fu, P. Gong, K. Yao, D. Lu, W. Chen, Y. Liu, Y. Yang, J. Xiao, S. Wu, Z. Geng, M. Huang, X. Zhang, R. Hutton, L. Liljeby, M. He, and Y. Zou, *Can. J. Phys.* **86**, in press (2008).
- [54] G. Zschornack, S. Landgraf, F. Grossmann, U. Kentsch, V. Ovsyannikov, M. Schmidt, and F. Ullmann, *Nucl. Instrum. Methods Phys. Res. B* **235**, 160 (2005).
- [55] T. Werner, G. Zschornack, F. Großmann, V. Ovsyannikov, and F. Ullmann, *Phys. Scripta* **T92**, 241 (2001).
- [56] J. D. Silver, A. J. Varney, H. S. Margolis, P. E. G. Baird, I. P. Grant, P. D. Groves, W. A. Hallet, A. T. Handford, P. J. Hirst, A. R. Holmes, D. J. H. Howie, R. A. Hunt, K. A. Nobbs, M. Roberts, W. Studholme, J. S. Wark, M. T. Williams, M. A. Levine, D. D. Dietrich, W. G. Graham, I. D. Williams, R. O'Neill, and S. J. Rose, *Rev. Sci. Instrum.* **65**, 1072 (1994).
- [57] D. J. Bieber, H. S. Margolis, P. K. Oxley, and J. D. Silver, *Phys. Scripta* **T73**, 64 (1997).
- [58] M. R. Tarbutt, R. Barnsley, N. J. Peacock, and J. D. Silver, *J. Phys. B* **34**, 3979 (2001).
- [59] M. R. Tarbutt and J. D. Silver, *J. Phys. B* **35**, 1467 (2002).
- [60] K. Hosaka, D. N. Crosby, K. Gaarde-Widdowson, C. J. Smith, J. D. Silver, T. Kinugawa, S. Ohtani, and E. G. Myers, *Phys. Rev. A* **69**, 011802 (2004).
- [61] N. Nakamura, J. Asada, F. J. Currell, T. Fukami, T. Hirayama, D. Kato, K. Motohashi, E. Nojikawa, S. Ohtani, K. Okasaki, M. Sakurai, H. Shimizu, N. Tada, S. Tsurubuchi, and H. Watanabe, *Rev. Sci. Instrum.* **69**, 694 (1998).
- [62] N. Nakamura, H. Tobiyama, H. Nohara, D. Kato, H. Watanabe, F. Currell, and S. Ohtani, *Phys. Rev. A* **73**, 020705 (2006).
- [63] H. Watanabe, S. Takahashi, M. Tona, N. Yoshiyasu, N. Nakamura, M. Sakurai, C. Yamada, and S. Ohtani, *Phys. Rev. A* **74**, 042901 (2006).
- [64] N. Nakamura, D. Kato, and S. Ohtani, *Phys. Rev. A* **61**, 052510 (2000).
- [65] D. Kato, N. Nakamura, S. Ohtani, and A. Sasaki, *Phys. Scripta* **T92**, 126 (2001).
- [66] P. Beiersdorfer, M. Bitter, S. von Goeler, S. Cohen, K. W. Hill, J. Timberlake, R. S. Walling, M. H. Chen, P. L. Hagelstein, and J. H. Scofield, *Phys. Rev. A* **34**, 1297 (1986).



- [67] P. Beiersdorfer, S. von Goeler, M. Bitter, E. Hinnov, R. Bell, S. Bernabei, J. Felt, K. W. Hill, R. Hulse, S. S. J. Stevens, A. W. J. Timberlake and, M. H. Chen, J. H. Scofield, D. D. Dietrich, M. Gerassimenko, E. Silver, R. S. Walling, and P. L. Hagelstein, *Phys. Rev. A* **37**, 4153 (1988).
- [68] N. Nakamura, D. Kato, and S. Ohtani, *Nucl. Instrum. Methods Phys. Res. B* **205**, 57 (2003).
- [69] K. Widmann, P. Beiersdorfer, G. V. Brown, J. Crespo López-Urrutia, K. J. Reed, J. H. Scofield, and S. B. Utter, (in *X-ray and Innershell Processes*, ed. ed. by R. W. Dunford et al., AIP Conf. Proc. No. 506 (American Institute of Physics, New York, 2000), p. 444–466).
- [70] N. Nakamura, T. Nakahara, and S. Ohtani, *J. Phys. Soc. Japan* **72**, 1650 (2003).
- [71] J. R. Henderson, P. Beiersdorfer, C. L. Bennett, S. Chantrenne, D. A. Knapp, R. E. Marrs, M. B. Schneider, K. L. Wong, G. A. Doschek, J. F. Seely, C. M. Brown, R. E. LaVilla, J. Dubau, and M. A. Levine, *Phys. Rev. Lett.* **65**, 705 (1990).
- [72] P. Beiersdorfer, D. A. Vogel, K. J. Reed, V. Decaux, J. H. Scofield, K. Widmann, G. Hölzer, E. Förster, O. Wehrhan, D. W. Savin, and L. Schweikhard, *Phys. Rev. A* **53**, 3974 (1996).
- [73] P. Beiersdorfer, G. Brown, S. Utter, P. Neill, K. J. Reed, A. J. Smith, and R. S. Thoe, *Phys. Rev. A* **60**, 4156 (1999).
- [74] E. Takács, E. S. Meyer, J. D. Gillaspy, J. R. Roberts, C. T. Chandler, L. T. Hudson, R. D. Deslattes, C. M. Brown, J. M. Laming, J. Dubau, and M. K. Inal, *Phys. Rev. A* **54**, 1342 (1996).
- [75] P. Beiersdorfer, in *Proceedings of the US-Japan Workshop and International Seminar on Plasma Polarization Spectroscopy, Kyoto, Japan, Jan. 26–28, 1998*, NIFS-PROC-37, eds. T. Fujimoto and P. Beiersdorfer, (National Institute for Fusion Science, Toki, Gifu, 1998), p. 67–89.
- [76] N. Nakamura, D. Kato, N. Miura, T. Nakahara, and S. Ohtani, *Phys. Rev. A* **63**, 024501 (2001).
- [77] D. L. Robbins, A. Y. Faenov, T. A. Pikuz, H. Chen, P. Beiersdorfer, M. J. May, J. Dunn, K. J. Reed, and A. J. Smith, *Phys. Rev. A* **70**, 022715 (2004).
- [78] C. Biedermann, A. Förster, G. Fußmann, and R. Radtke, *Phys. Scripta* **T73**, 360 (1997).
- [79] R. Radtke, C. Biedermann, T. Fuchs, G. Fußmann, and P. Beiersdorfer, *Phys. Rev. E* **61**, 1966 (2000).
- [80] R. Radtke, C. Biedermann, P. Mandelbaum, and J. L. Schwob, *J. Phys. Conf. Ser.* **58**, 113 (2007).
- [81] N. J. Peacock, M. G. O Mullane, R. Barnsley, and M. R. Tarbutt, *Can. J. Phys.* **86**, in press (2008).
- [82] C. H. Skinner, *Can. J. Phys.* **86**, in press (2008).
- [83] C. Biedermann, R. Radtke, G. Fußmann, P. Mandelbaum, and J. L. Schwob, *Nucl. Instrum. Methods Phys. Res. B* **235**, 126 (2005).
- [84] J. D. Gillaspy, *Phys. Scripta* **T71**, 99 (1997).

- [85] C. A. Morgan, F. G. Serpa, E. Takács, E. S. Meyer, J. D. Gillaspy, J. Sugar, J. R. Roberts, C. M. Brown, and U. Feldman, Phys. Rev. Lett. **74**, 1716 (1995).
- [86] J. V. Porto, I. Kink, and J. D. Gillaspy, Phys. Rev. A **61**, 054501 (2000).
- [87] H. Watanabe, D. Crosby, F. Currell, T. Fukami, D. Kato, S. Ohtani, J. Silver, and C. Yamada, Phys. Rev. A **63**, 042513 (2001).
- [88] S. B. Utter, P. Beiersdorfer, and E. Träbert, Phys. Rev. A **67**, 012508 (2003).
- [89] D. Kato, T. Fukami, T. Kinugawa, S. Ohtani, H. Watanabe and C. Yamada, in *Proceedings of the International Seminar on Atomic Processes in Plasmas, July 29-30, 1999, Toki, Japan*, NIFS-PROC-44, ed. I. Murakami and T. Kato, (National Institute of Fusion Science, Toki, 2000)., .
- [90] P. Beiersdorfer, S. B. Utter, K. L. Wong, J. R. Crespo López-Urrutia, J. A. Britten, H. Chen, C. L. Harris, R. S. Thoe, D. B. Thorn, E. Träbert, M. G. H. Gustavsson, C. Forssén, and A.-M. Mårtensson-Pendrill, Phys. Rev. A **64**, 032506 (2001).
- [91] P. Beiersdorfer, J. R. Crespo López-Urrutia, S. B. Utter, E. Träbert, M. Gustavsson, C. Forssén, and A.-M. Mårtensson-Pendrill, Nucl. Instrum. Methods **B 205**, 62 (2003).
- [92] E. Takács, B. Blagojevic, K. Makónyi, E.-O. Le Bigot, C. I. Szabó, Y.-K. Kim, and J. D. Gillaspy, Phys. Rev. A **73**, 052505 (2006).
- [93] J. R. Crespo López-Urrutia, P. Beiersdorfer, K. Widmann, and V. Decaux, Can. J. Phys. **80**, 1687 (2002).
- [94] C. Biedermann and R. Radtke, Phys. Rev. A **75**, 066501 (2007).
- [95] P. Beiersdorfer, G. V. Brown, J. J. Drake, M.-F. Gu, S. M. Kahn, J. K. Lepson, D. A. Liedahl, C. W. Mauche, D. W. Savin, S. B. Utter, and B. J. Wargelin, Revista Mexicana Astronomía y Astrofísica **9**, 123 (2000).
- [96] G. V. Brown, P. Beiersdorfer, D. A. Liedahl, K. Widmann, S. M. Kahn, and E. J. Clothiaux, Ap. J. Suppl. **140**, 589 (2002).
- [97] I. Kink, J. M. Laming, E. Takács, J. V. Porto, J. D. Gillaspy, E. Silver, H. Schopper, S. R. Bandler, M. Barbera, N. Brickhouse, S. Murray, N. Madden, D. Landis, J. Beeman, and E. E. Haller, Phys. Scripta **T92**, 454 (2001).
- [98] J. M. Laming, I. Kink, E. Takacs, J. V. Porto, J. D. Gillaspy, E. H. Silver, H. W. Schopper, S. R. Bandler, N. S. Brickhouse, S. S. Murray, M. Barbera, A. K. Bhatia, G. A. Doschek, N. Madden, D. Landis, J. Beeman, and E. E. Haller, Astrophys. J. **545**, L161 (2000).
- [99] P. Beiersdorfer, E. Behar, K. R. Boyce, G. V. Brown, H. Chen, K. C. Gendreau, M.-F. Gu, J. Gyga, S. M. Kahn, R. L. Kelley, F. S. Porter, C. K. Stahle, and A. E. Szymkowiak, Astrophys. J. (Lett.) **576**, L169 (2002).

- [100] P. Beiersdorfer, M. Bitter, S. von Goeler, and K. W. Hill, *Astrophys. J.* **610**, 616 (2004).
- [101] G. X. Chen, K. Kirby, E. Silver, N. S. Brickhouse, J. D. Gillaspy, J. N. Tan, J. M. Pomeroy, and J. M. Laming, *Phys. Rev. Lett.* **97**, 143201 (2006).
- [102] G. V. Brown, P. Beiersdorfer, and K. Widmann, *Phys. Rev. A* **63**, 032719 (2001).
- [103] M.-F. Gu, P. Beiersdorfer, G. V. Brown, H. Chen, K. R. Boyce, R. L. Kelley, C. A. Kilbourne, F. S. Porter, and S. M. Kahn, *Astrophys. J. (Lett.)* **607**, L143 (2004).
- [104] G. X. Chen, K. Kirby, E. Silver, N. S. Brickhouse, J. D. Gillaspy, J. N. Tan, J. M. Pomeroy, and J. M. Laming, *Phys. Rev. Lett.* **99**, 109902 (2007).
- [105] S. W. Epp, J. R. Crespo López-Urrutia, G. Brenner, V. Mäkel, P. H. Mokler, R. Treusch, M. Kuhlmann, M. V. Yurkov, J. Feldhaus, J. R. Schneider, M. Wellhöfer, M. Martins, W. Wurth, and J. Ullrich, *Phys. Rev. Lett.* **98**, 183001 (2007).
- [106] I. Draganić, J. R. Crespo López-Urrutia, R. DuBois, S. Fritzsche, V. M. Shabaev, R. Soria Orts, I. I. Tupitsyn, Y. Zou, and J. Ullrich, *Phys. Rev. Lett.* **91**, 183001 (2003).
- [107] P. Beiersdorfer, V. Decaux, S. Elliott, K. Widmann, and K. Wong, *Rev. Sci. Instrum.* **66**, 303 (1995).
- [108] P. Beiersdorfer, A. L. Osterheld, V. Decaux, and K. Widmann, *Phys. Rev. Lett.* **77**, 5353 (1996).
- [109] R. Soria Orts, Z. Harman, J. R. Crespo López-Urrutia, A. N. Artemyev, H. Bruhns, A. J. González Martínez, U. D. Jentschura, C. H. Keitel, A. Lapierre, V. Mironov, V. M. Shabaev, H. Tawara, I. I. Tupitsyn, J. Ullrich, and A. V. Volotka, *Phys. Rev. Lett.* **97**, 103002 (2006).
- [110] A. Lapierre, U. D. Jentschura, J. R. Crespo López-Urrutia, J. Braun, G. Brenner, H. Bruhns, D. Fischer, A. J. González Martínez, Z. Harman, W. R. Johnson, C. H. Keitel, V. Mironov, C. J. Osborne, G. Sikler, R. Soria Orts, V. Shabaev, H. Tawara, I. I. Tupitsyn, J. Ullrich, and Volotka, *Phys. Rev. Lett.* **95**, 183001 (2005).
- [111] E. Träbert, P. Beiersdorfer, S. B. Utter, G. V. Brown, H. Chen, C. L. Harris, P. A. Neill, D. W. Savin, and A. J. Smith, *Astrophys. J.* **541**, 506 (2000).
- [112] D. P. Moehs and D. A. Church, *Phys. Rev. A* **58**, 1111 (1998).
- [113] F. G. Serpa, J. D. Gillaspy, and E. Träbert, *J. Phys. B* **31**, 3345 (1998).
- [114] G. Brenner, J. R. Crespo López-Urrutia, Z. Harman, P. H. Mokler, and J. Ullrich, *Phys. Rev. Lett.* **75**, 032504 (2007).
- [115] P. Beiersdorfer, E. Träbert, and E. H. Pinnington, *Astrophys. J.* **587**, 836 (2003).
- [116] S. J. Smith, A. Chutjian, and J. A. Lozano, *Phys. Rev. A* **72**, 062504 (2005).
- [117] D. P. Moehs and D. A. Church, *Astrophys. J. (Lett.)* **516**, L111 (1999).

- [118] E. Träbert, G. Gwinner, A. Wolf, E. J. Knystautas, H.-P. Garnir, and X. Todor, J. Phys. B **35**, 671 (2002).
- [119] M. Bitter, K. W. Hill, S. von Goeler, W. Stodiek, P. Beiersdorfer, J. E. Rice, and A. Ince-Cushman, Can. J. Phys. **86**, in press (2008).
- [120] M. B. Schneider, R. Mancini, K. Widmann, K. Fournier, G. V. Brown, H.-K. Chung, H. A. Baldis, K. Cone, J. Dunn, S. B. Hansen, M. J. May, D. Thorn, and P. Beiersdorfer, Can. J. Phys. **86**, in press (2008).
- [121] M. J. May, P. Beiersdorfer, G. V. Brown, K. Fournier, M. Gu, S. B. Hansen, M. Schneider, J. H. Scofield, S. Terracol, K. J. Reed, B. Wilson, K. L. Wong, K. R. Boyce, R. Kelley, C. A. Kilbourne, and F. S. Porter, Can. J. Phys. **86**, in press (2008).
- [122] A. S. Safronova, V. L. Kantsyrev, P. Neill, U. I. Safronova, D. A. Fedin, N. D. Ouart, M. F. Yilmaz, G. Osborne, I. Shrestha, K. Williamson, T. Hoppe, C. Harris, P. Beiersdorfer, and S. Hansen, Can. J. Phys. **86**, in press (2008).
- [123] P. Beiersdorfer, Ann. Rev. Astron. Astrophys. **41**, 343 (2003).
- [124] J. Lepson, P. Beiersdorfer, M. Bitter, and S. M. Kahn, Can. J. Phys. **86**, in press (2008).
- [125] B. J. Wargelin, P. Beiersdorfer, and G. V. Brown, Can. J. Phys. **86**, in press (2008).
- [126] H. Chen and P. Beiersdorfer, Can. J. Phys. **86**, in press (2008).
- [127] J. Sapirstein and K. Cheng, Can. J. Phys. **86**, in press (2008).
- [128] E. Träbert, Can. J. Phys. **86**, in press (2008).
- [129] B. J. Wargelin, P. Beiersdorfer, and S. M. Kahn, Phys. Rev. Lett. **71**, 2196 (1993).
- [130] J. R. Crespo López-Urrutia, P. Beiersdorfer, and K. Widmann, Phys. Rev. A **74**, 012507 (2006).
- [131] P. Beiersdorfer, A. L. Osterheld, J. Scofield, B. Wargelin, , and R. E. Marrs, Phys. Rev. Lett. **67**, 2272 (1991).
- [132] Y. Ralchenko, J. N. Tan, J. D. Gillaspay, and J. M. Pomeroy, Phys. Rev. A **74**, 042514 (2006).
- [133] E. Träbert, P. Beiersdorfer, G. V. Brown, K. Boyce, R. L. Kelley, C. A. Kilbourne, F. S. Porter, and A. Szymkowiak, Phys. Rev. A **73**, 022508 (2006).
- [134] K. Yao, M. Andersson, T. Brage, R. Hutton, P. Jönsson, and Y. Zou, Phys. Rev. Lett. **98**, 269903(E) (2007).
- [135] E. Träbert, P. Beiersdorfer, and G. V. Brown, Phys. Rev. Lett. **98**, 263001 (2007).
- [136] I. Bergström, C. Carlberg, T. Fritioff, G. Douysset, J. Schönfelder, and R. Schuch, Nucl. Instrum. Methods Phys. Res. A **487**, 618 (2002).

- [137] T. Stöhlker, H. Backe, H. F. Beyer, F. Bosch, A. Bräuning-Demian, S. Hagmann, D. C. Ionescu, K. Jungmann, H. J. Kluge, C. Kozhuharov, T. Köhl, D. Liesen, R. Mann, P. H. Mokler, and W. Quint, Nucl. Instrum. Methods Phys. Res. B **205**, 156 (2003).
- [138] F. J. Currell, J. Aiken, K. F. Dunn, T. Kavanagh, V. Krastev, X. Lu, M. Matranga, A. F. Morton, B. E. O'Rourke, H. Tawara, and H. Watanabe, Phys. Scripta **T120**, 53 (2005).
- [139] U. Kentsch, T. Werner, G. Zschornack, F. Grossmann, V. P. Ovsyannikov, and F. Ullmann, Eur. Phys. J. D **17**, 297 (2001).
- [140] H. Watanabe, A. P. Kavanagh, H. Kuramoto, Y. M. Li, N. Nakamura, S. Ohtani, B. O'Rourke, A. Sato, H. Tawara, X. M. Tong, and F. J. Currell, Nucl. Instrum. Methods Phys. Res. B **235**, 261 (2005).
- [141] M. J. May, M. Finkenthal, V. Soukhanovskii, D. Stutman, H. W. Moos, D. Pacella, G. Mazzitelli, K. Fournier, W. Goldstein, and B. Gregory, Rev. Sci. Instrum. **70**, 375 (1999).

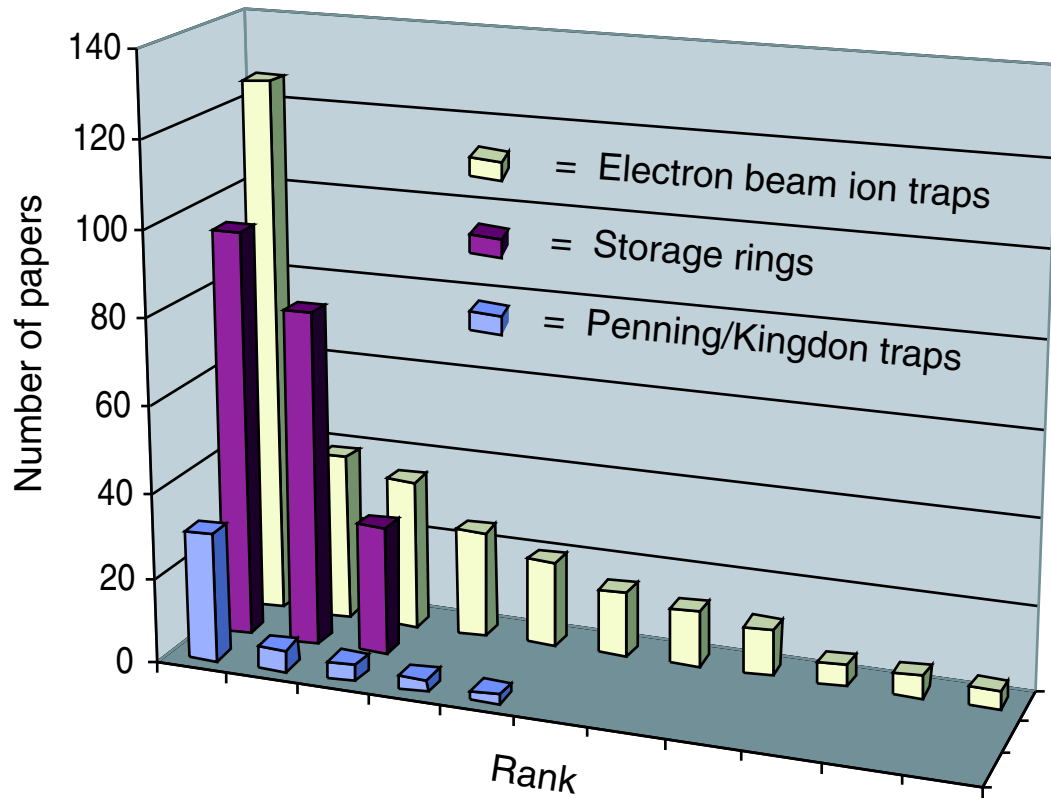


Figure 1: Number of papers published in physics and astronomy journals between 2000 and 2006 by different facilities utilizing trapped highly charged ions. The facilities leading the publication list in each category are the SMILETRAP Penning facility[136] at Stockholm University in Sweden, the Experimental Storage Ring heavy-ion storage ring facility at GSI Darmstadt in Germany [137], and the EBIT facility at Livermore in California [1].

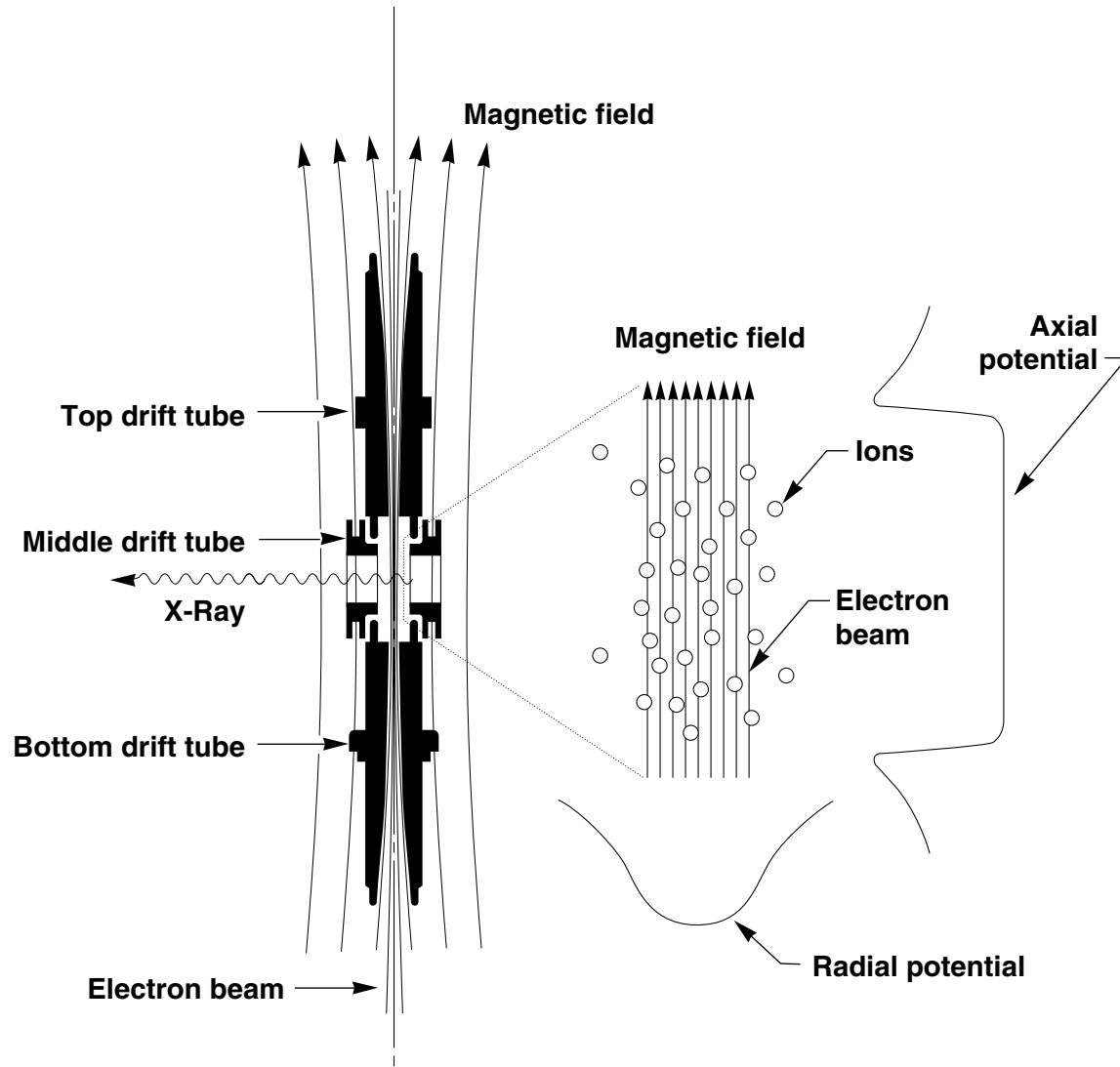


Figure 2: Schematic of the heart of an electron beam ion trap. The electron beam passing through the trap is compressed by a strong axial magnetic field. Ions are confined radially by the space charge of the electron beam and by axial magnetic field. They are confined axially by the electric potential applied to the top and bottom electrodes, i.e. to the top and bottom drift tubes. Axial slots in the middle drift tube allow an unimpeded view of the trapped ions.

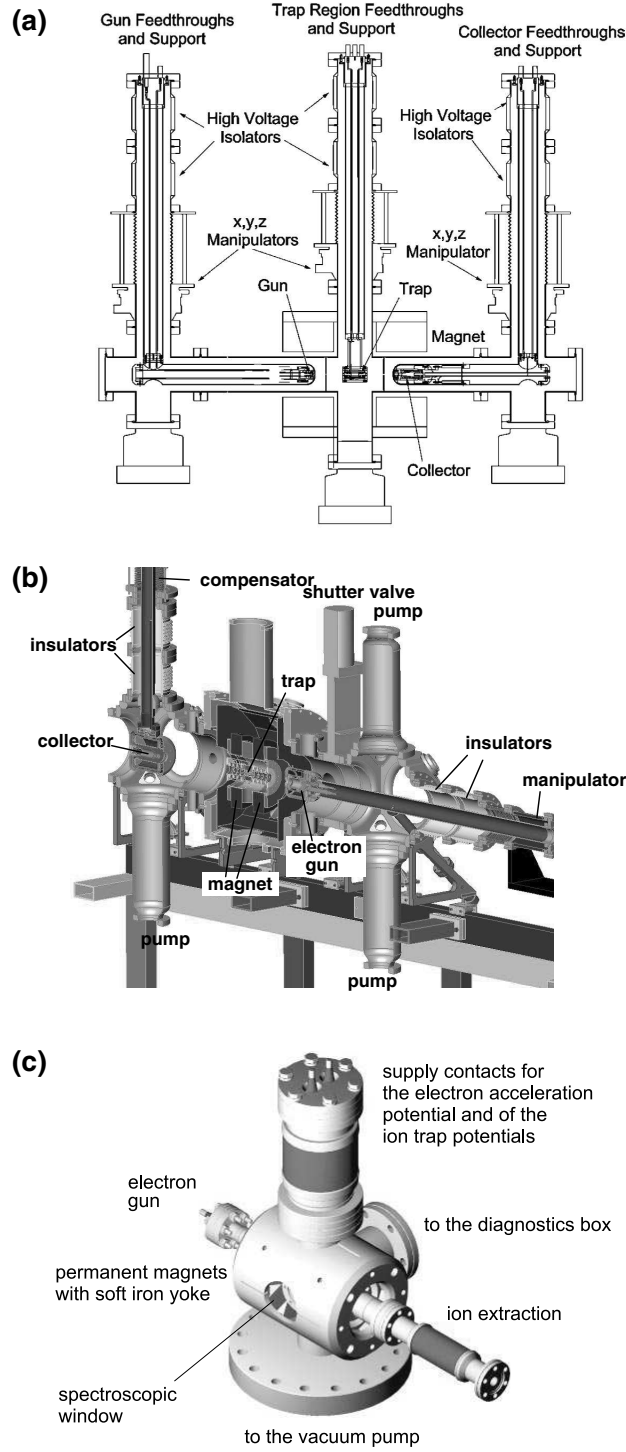


Figure 3: Schematics of electron beam ion traps deployed at (a) the Queen's University in Belfast, Northern Ireland [138], (b) the Tri-University Meson Facility (TRIUMF) in Vancouver, Canada, [12] and (c) the Technical University in Dresden, Germany [139].



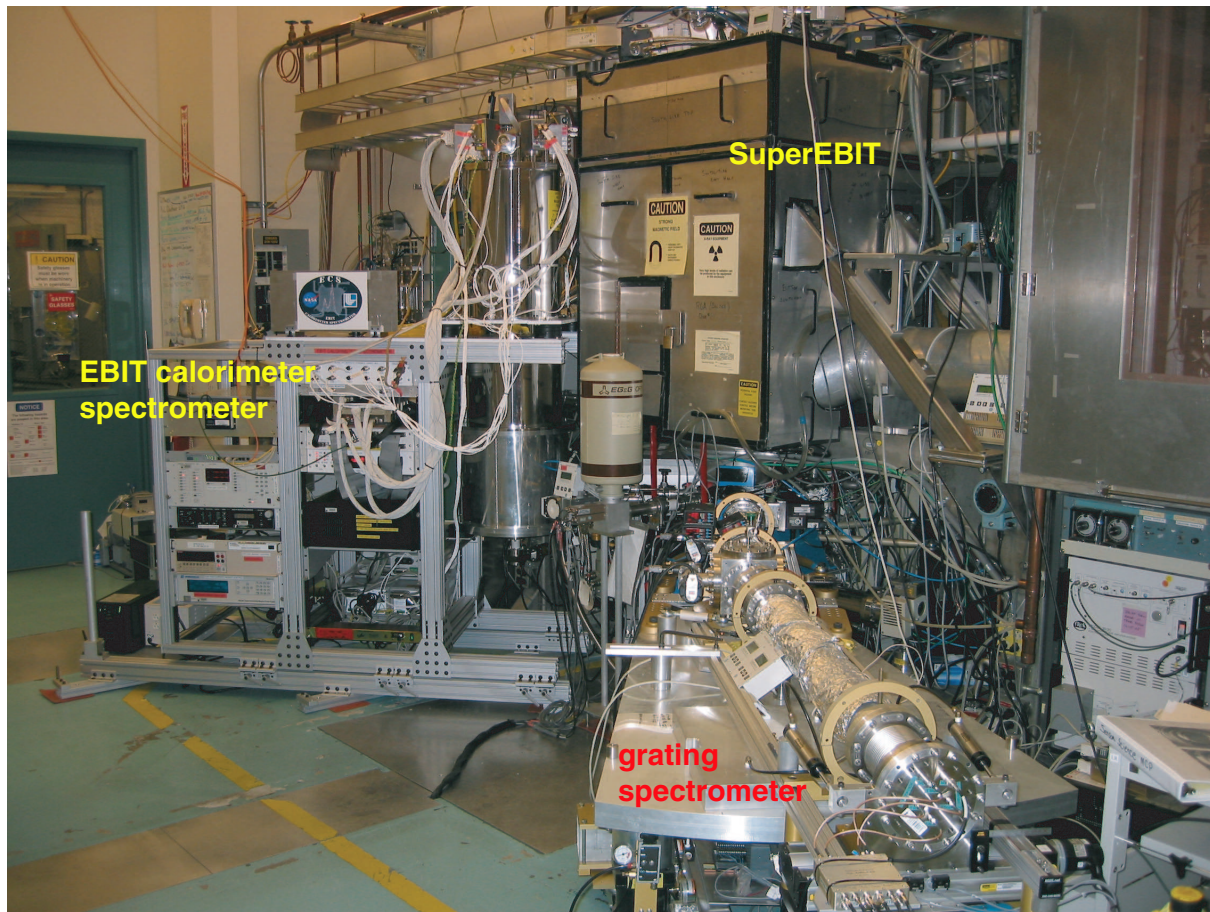


Figure 4: The SuperEBIT facility at the Lawrence Livermore National Laboratory and associated spectroscopic equipment in November 2007.

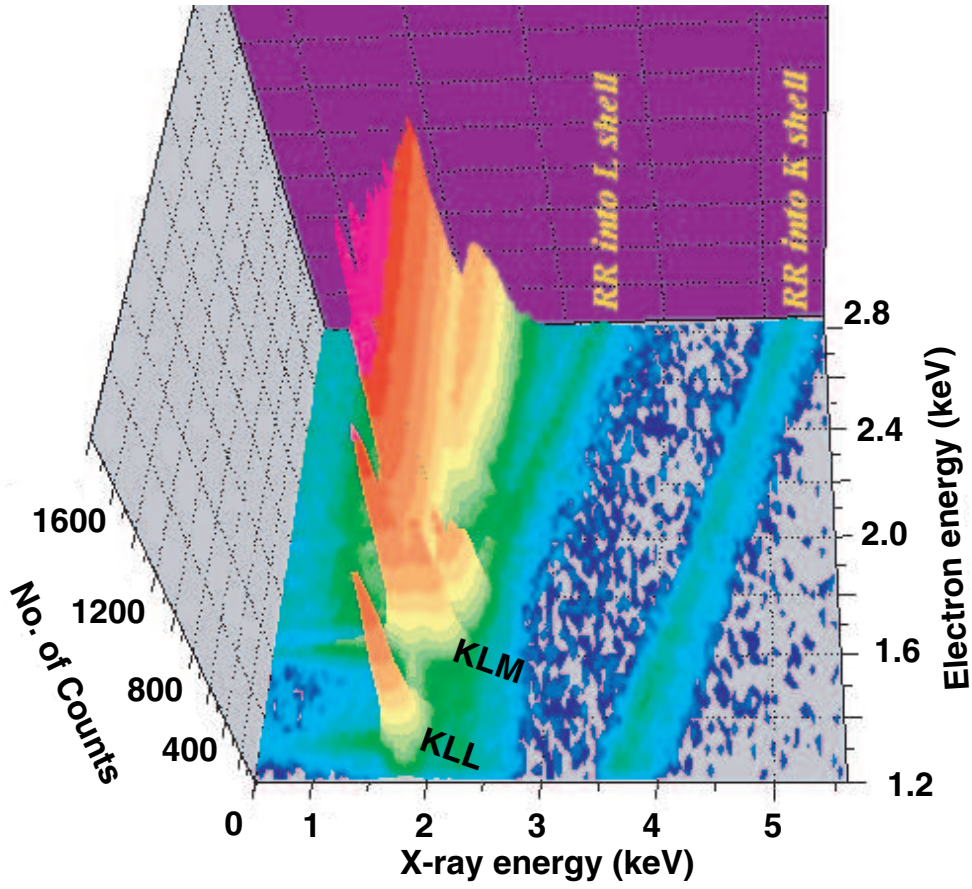


Figure 5: Scatter plot of the x-ray excitation function of near-heliumlike silicon ions. The measurement was made at the Stockholm electron beam ion trap facility using a solid-state detector and preparing the ions at a beam energy of 7 keV. (Courtesy of R. Schuch.)

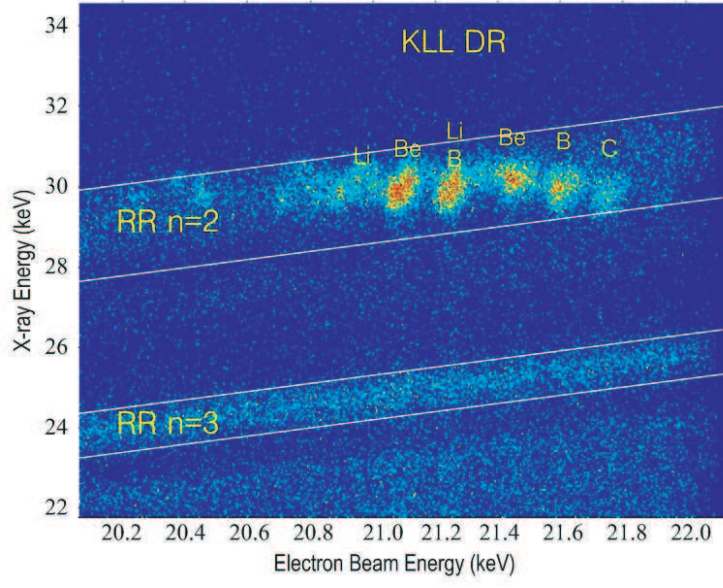


Figure 6: Scatter plot of the x-ray emission from KLL resonance processes involving L-shell xenon ions. The measurement was made at the Shanghai electron beam ion trap facility using a solid-state detector. From [53].

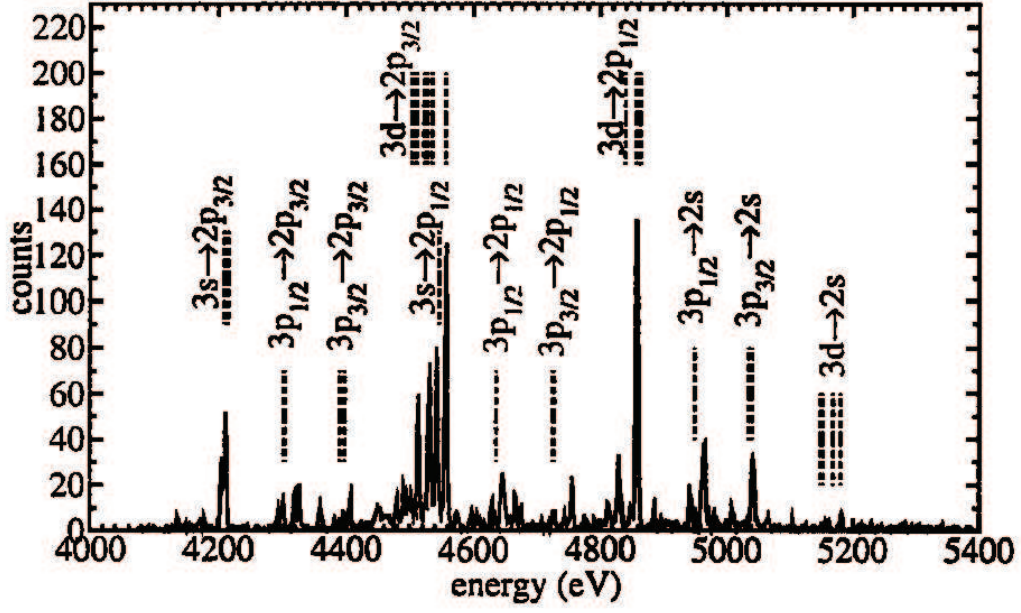


Figure 7: Spectrum of the L-shell emission of neonlike xenon. The measurement was made at the Dresden electron beam ion trap using a flat-crystal spectrometer. From [55].

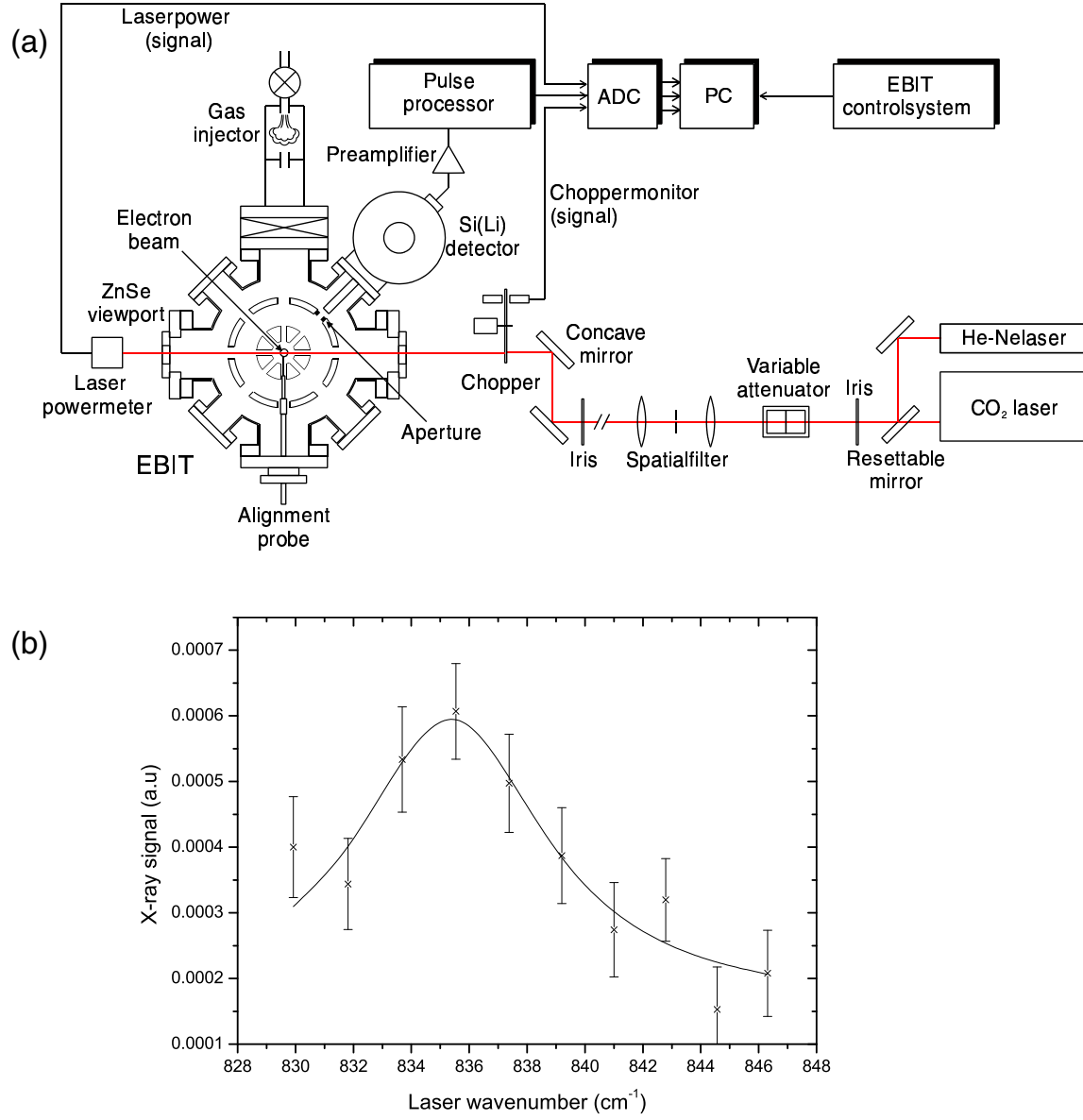


Figure 8: Measurement of the  $2s_{1/2}$ - $2p_{3/2}$  transition energy in  $\text{N}^{6+}$  using a laser probe: (a) Schematic of the experimental setup on the Oxford electron beam ion trap; (b) observed resonance. Adopted from [60].



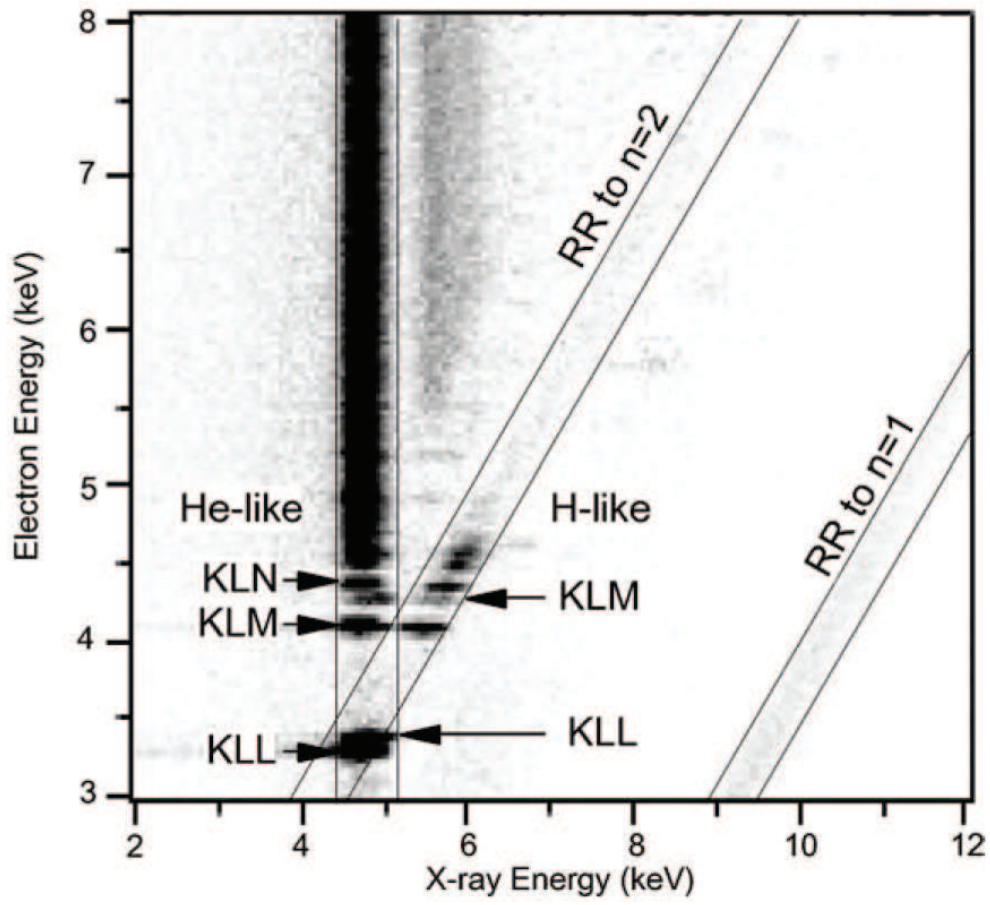


Figure 9: Scatter plot of the x-ray excitation function of heliumlike and hydrogenlike titanium ions. The measurement was made at the Tokyo electron beam ion trap facility using a solid-state detector. From [140].

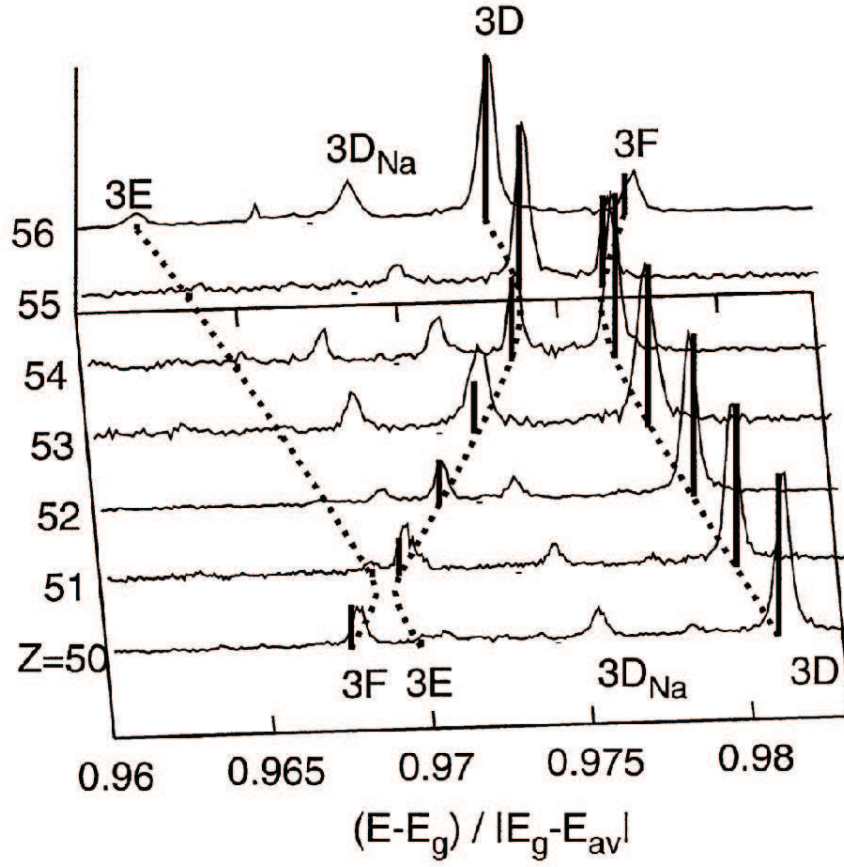


Figure 10: Crystal spectra of the neonlike ions with  $Z$  between 50 and 56 observed at the Tokyo electron beam ion trap. The three neonlike transitions affected by avoided level crossings involve the upper states  $(2p_{3/2}^5 3d_{3/2})_{(J=1)}$ ,  $(2p_{1/2}^5 3s_{3/2})_{(J=1)}$ , and  $(2p_{3/2}^5 3d_{5/2})_{(J=1)}$  and are labeled  $3E$ ,  $3F$ , and  $3D$ , respectively. From [65].

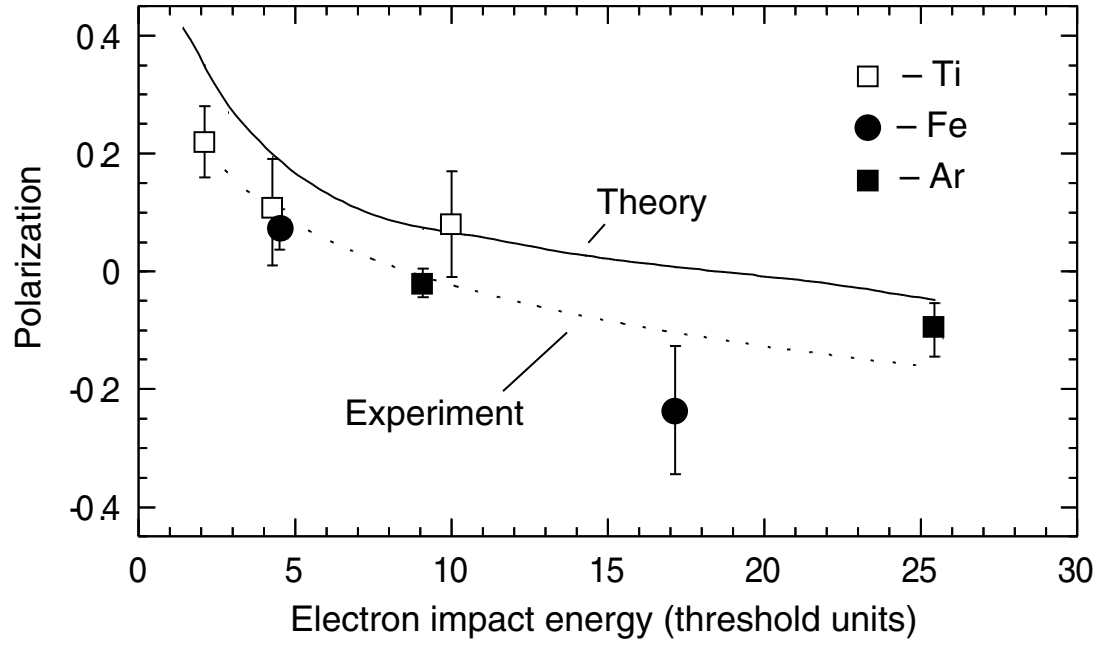


Figure 11: Measured polarization of the Lyman- $\alpha_1$  line of  $\text{Ar}^{17+}$  [77],  $\text{Ti}^{21+}$  [76], and  $\text{Fe}^{25+}$  [77] compared to the predictions of distorted-wave calculations as a function of electron-impact energy in threshold units. The dotted line represents the best fit of the experimental data.



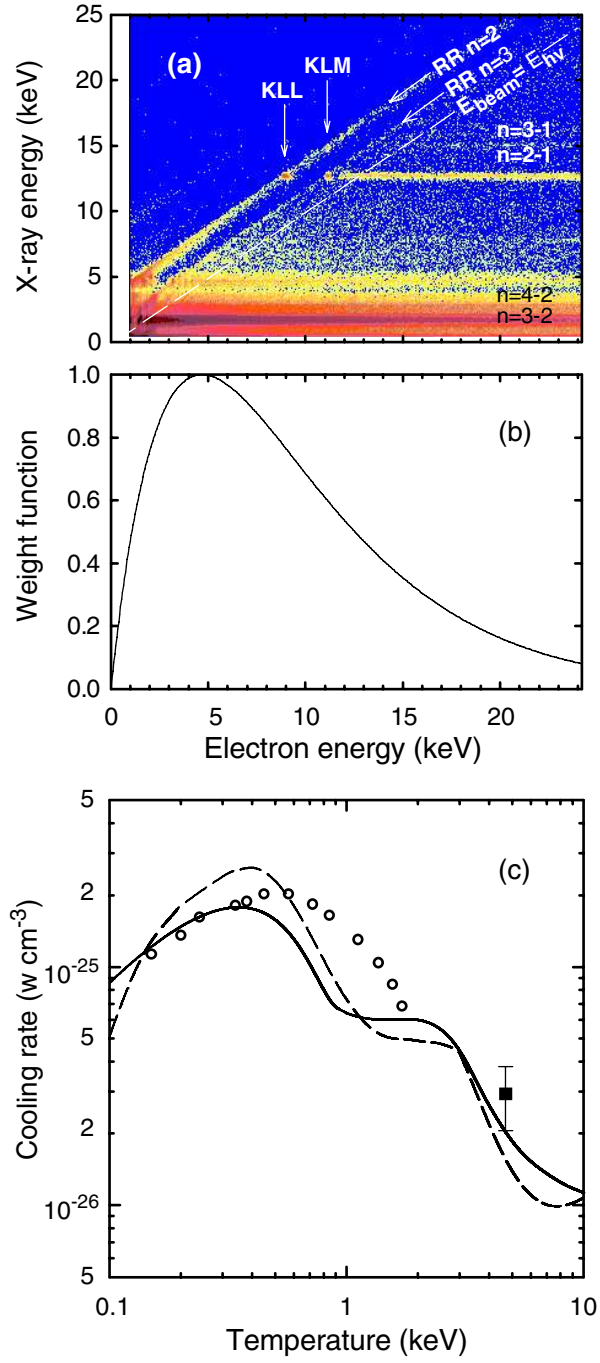


Figure 12: Measurement of the radiative cooling rate of krypton in a 4.7 keV plasma at the Berlin electron beam ion trap. (a) Scatter plot of the x-ray excitation function of krypton ions made with a solid-state detector; (b) weight function used to derive the cooling rate from (a); (c) radiative cooling rate of krypton as a function of plasma temperature. Solid and dashed curves are various calculations. The solid square is from the Berlin measurement [79]. The open circles are measurements from the Frascati tokamak [141].

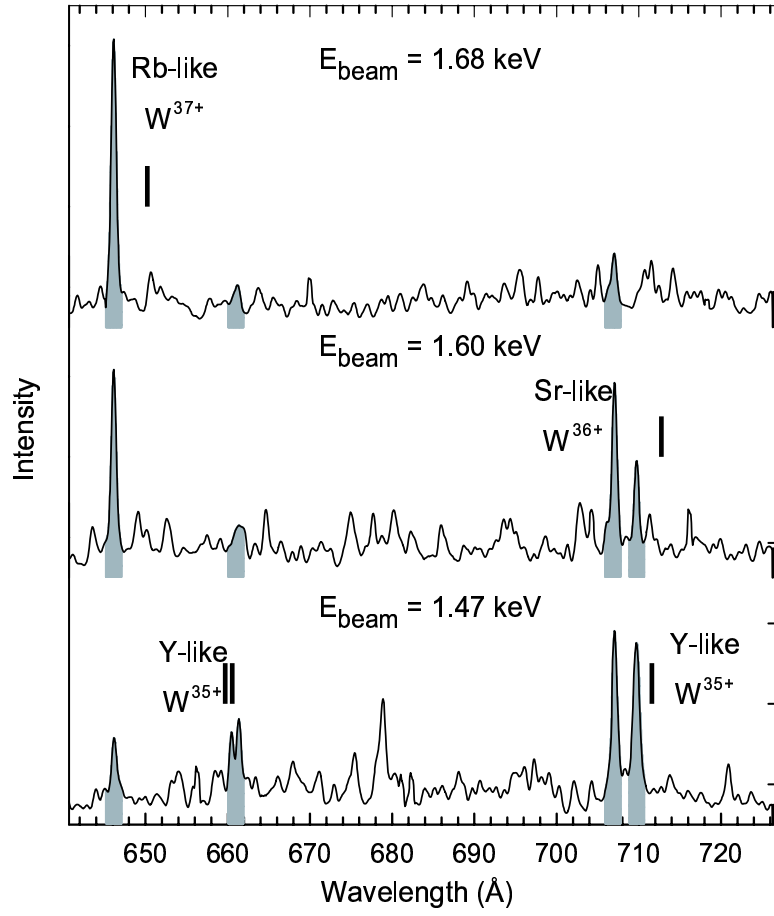


Figure 13: Measurements of FUV spectra of tungsten from the Berlin electron beam ion trap for different electron beam energies (adopted from [80]). Shaded lines are from tungsten; vertical marks indicate their positions predicted by calculations.

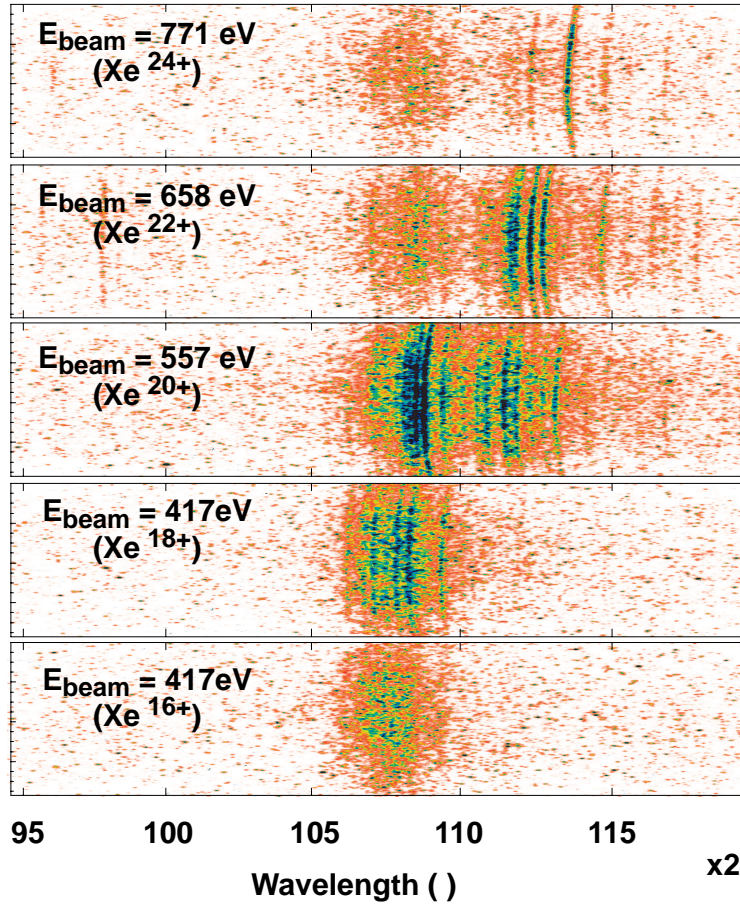


Figure 14: Measurements of EUV spectra of xenon from the Berlin electron beam ion trap for several electron beam energies (adopted from [83] and figures provided by C. Biedermann). The dominant charge state of xenon is indicated.

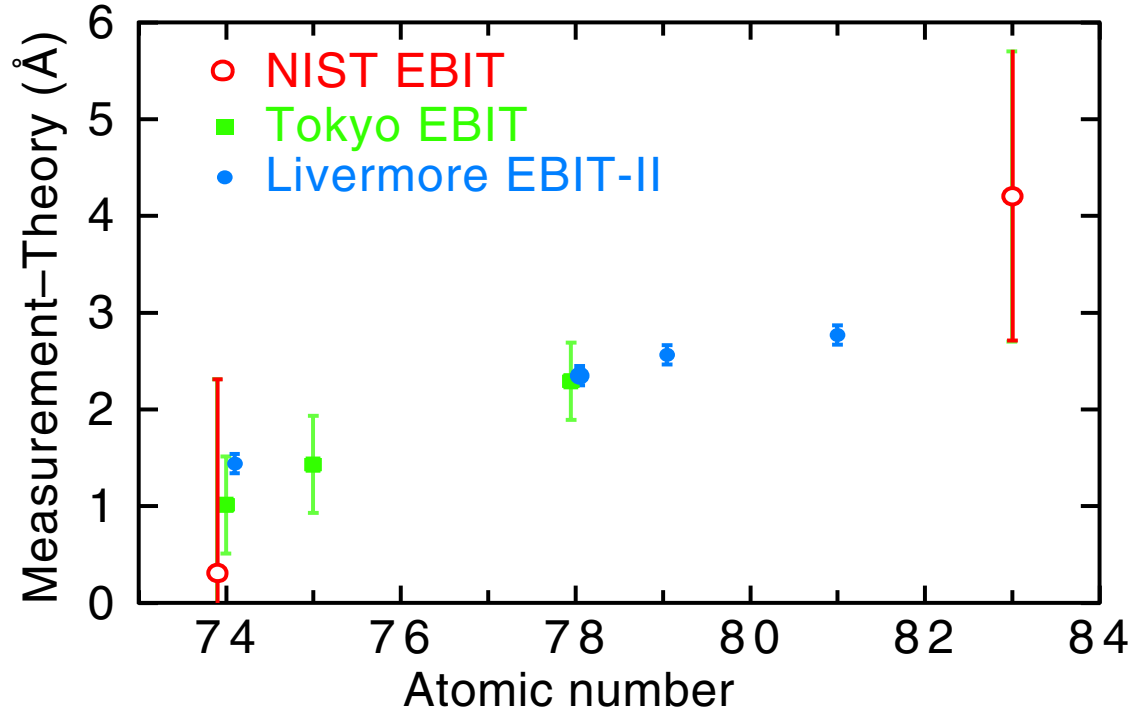


Figure 15: Difference between measured and predicted [89] wavelengths of the  $3d^4 \ ^2D_{3/2} - 3d^4 \ ^2D_{5/2}$  transition from titaniumlike ions. The measurements were performed at NIST (open circles) [86], Tokyo (solid squares) [87], and Livermore's EBIT-II device (solid circles) [88].

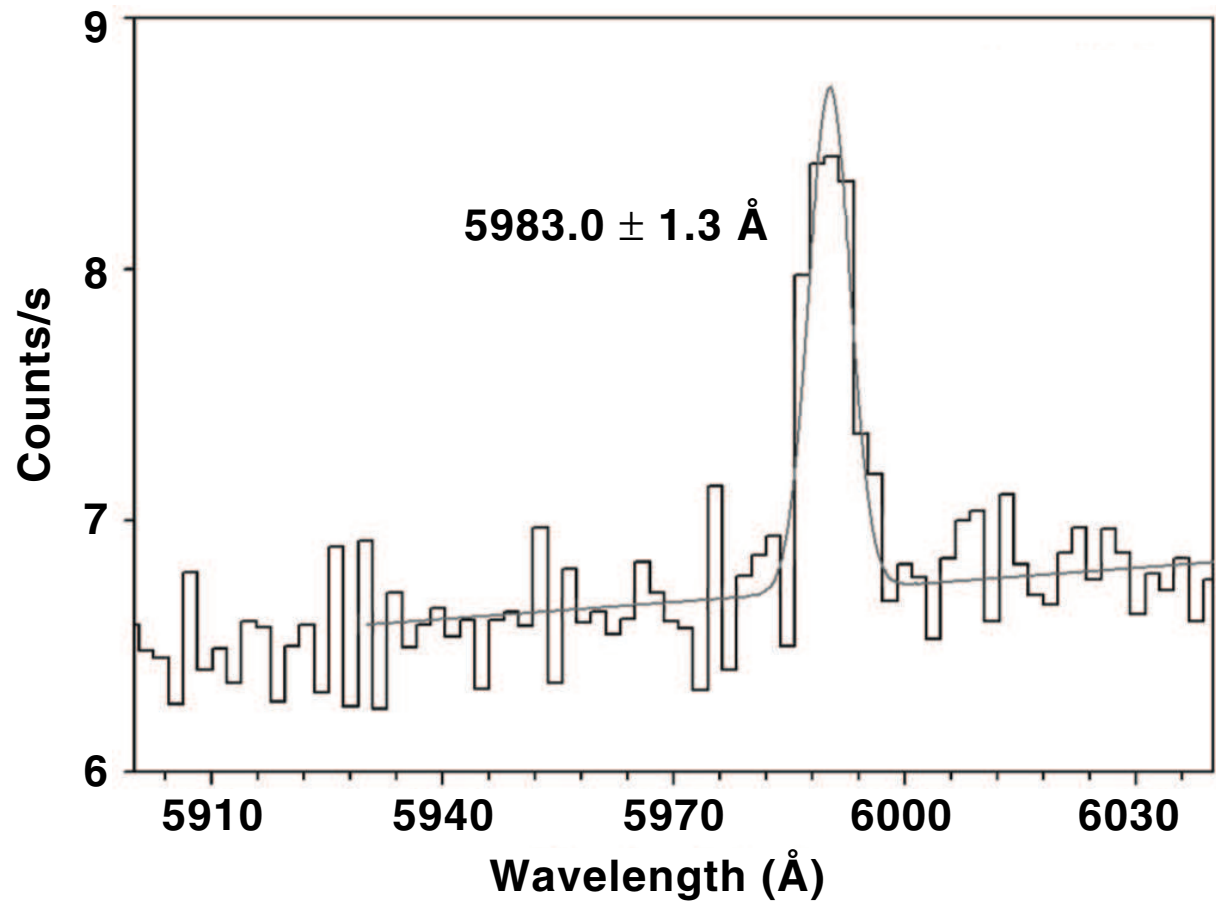


Figure 16: Measurement of the xenon emission at  $E_{beam} = 220$  eV from the Gaithersburg electron beam ion trap (adopted from [92]).

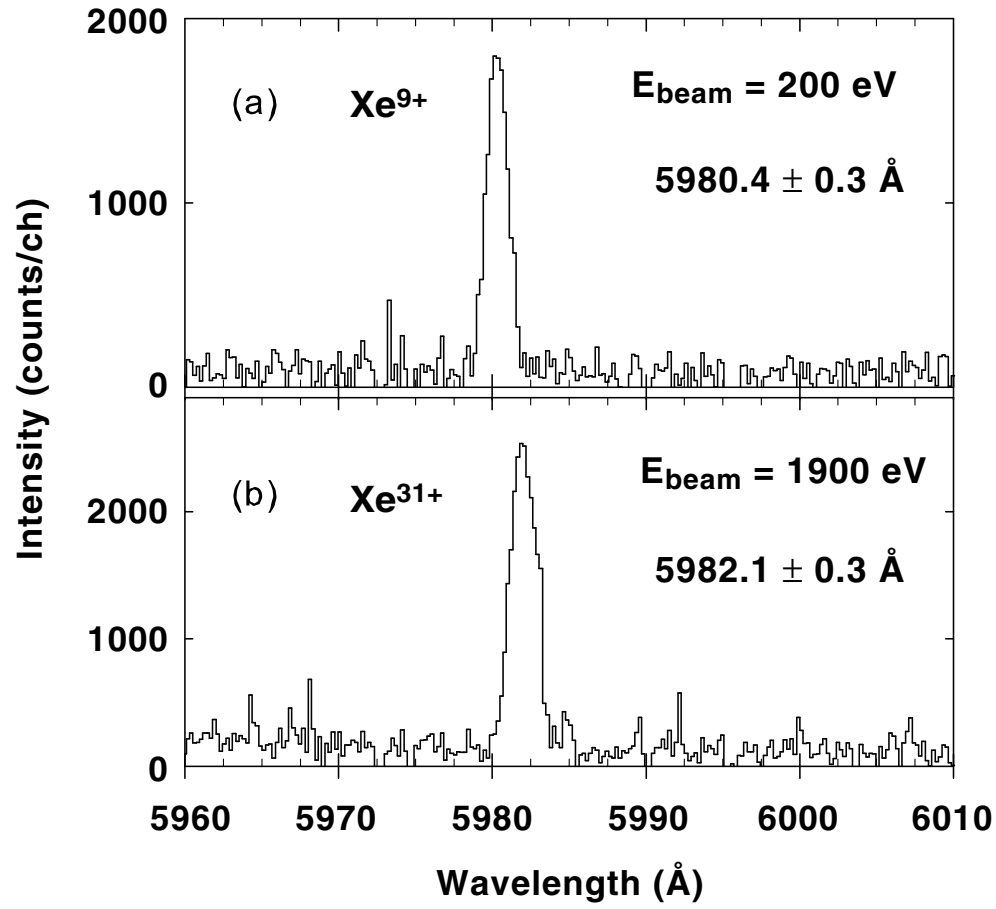


Figure 17: Measurements of the xenon emission at  $E_{\text{beam}} = 200 \text{ eV}$  and  $E_{\text{beam}} = 1900 \text{ eV}$  from the Berlin electron beam ion trap (adopted from [94]).

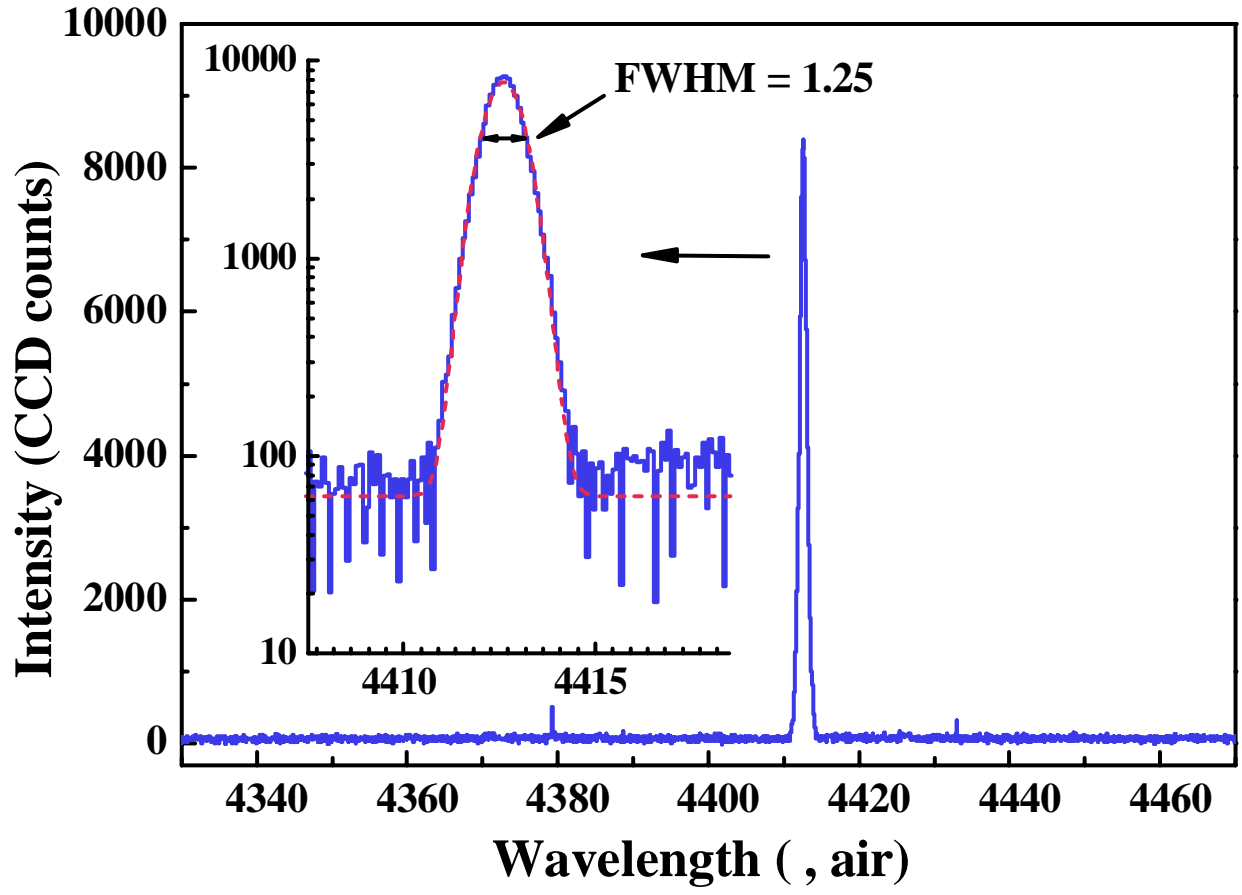


Figure 18: Measurement of the  $1s^2 2s^2 2p_{1/2} - 1s^2 2s^2 2p_{3/2}$  ground state fine structure transition in boronlike  $\text{Ar}^{13+}$  from the Heidelberg electron beam ion trap (adopted from [106]).

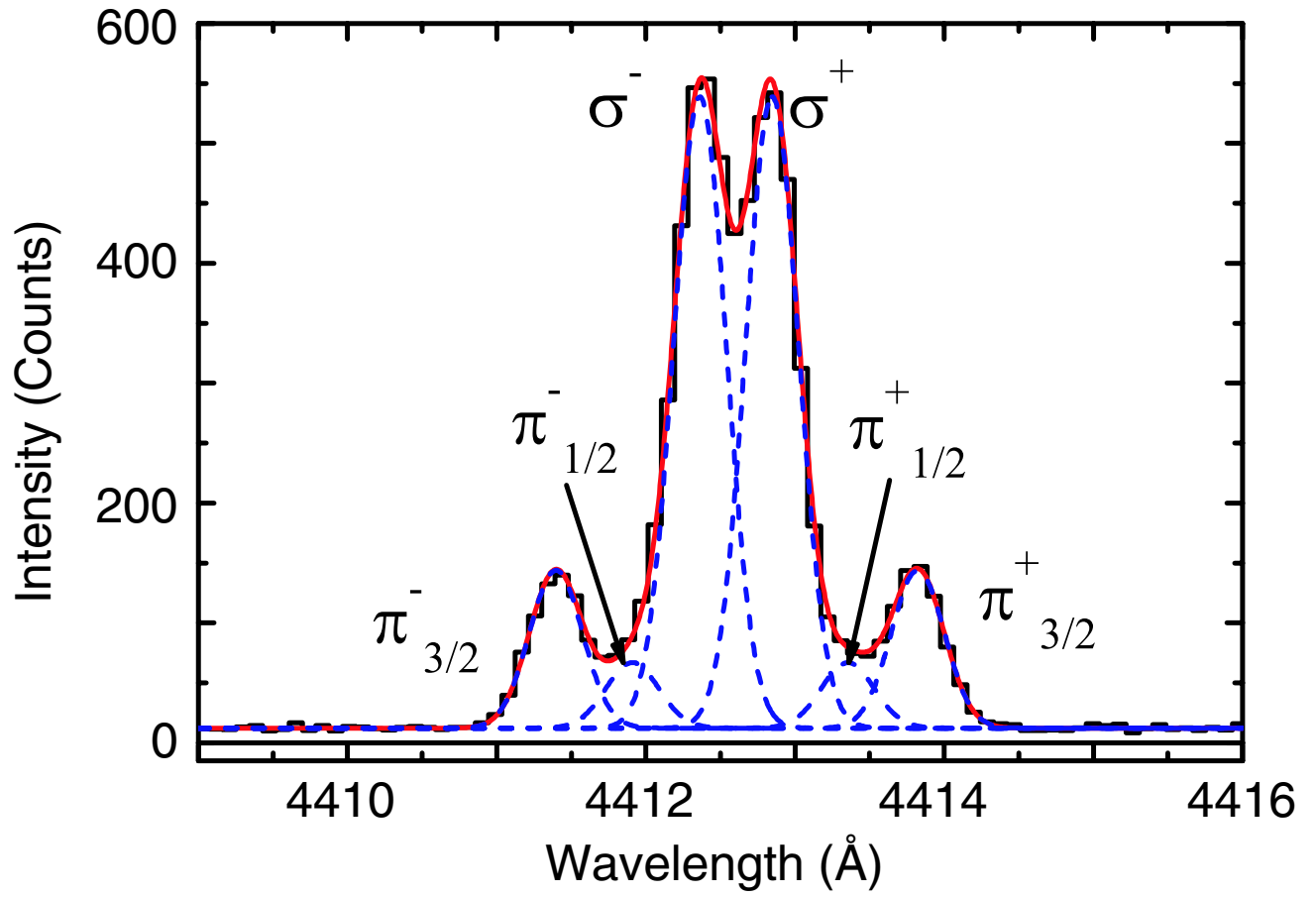


Figure 19: Measurement of the Zeeman components of the  $^2P_{1/2} - ^2P_{3/2}$  ground state fine structure transition in boronlike  $^{40}\text{Ar}^{13+}$  from the Heidelberg electron beam ion trap (adopted from [109]).



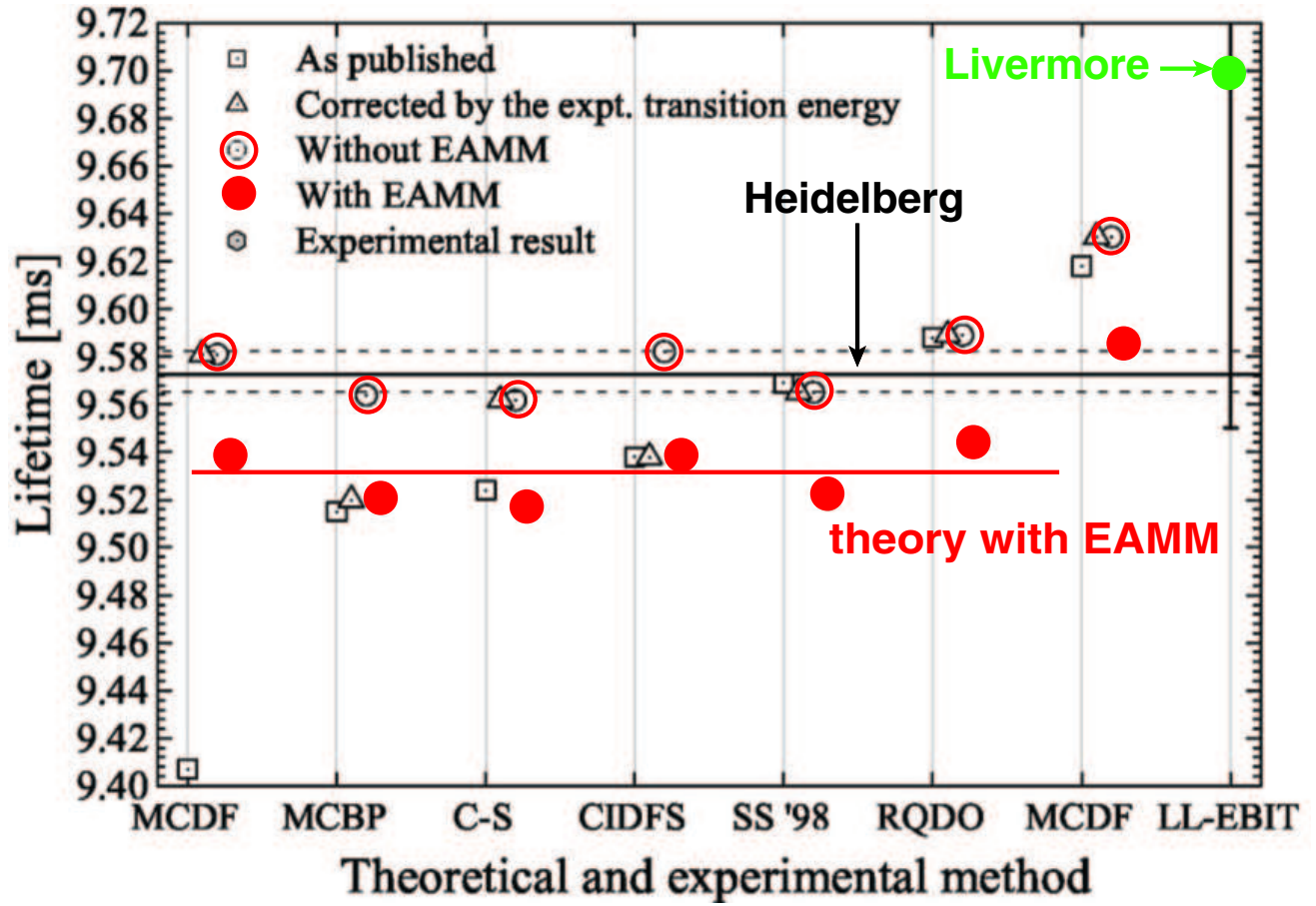


Figure 20: Comparison of the radiative rates of the  $1s^2 2s^2 2p_{1/2} - 1s^2 2s^2 2p_{3/2}$  ground state fine structure transition in boronlike  $\text{Ar}^{13+}$  measured at the Heidelberg electron beam ion trap with theory (adopted from [110]). Theoretical values with and without inclusion of the electron anomalous magnetic moment (EAMM) are shown.

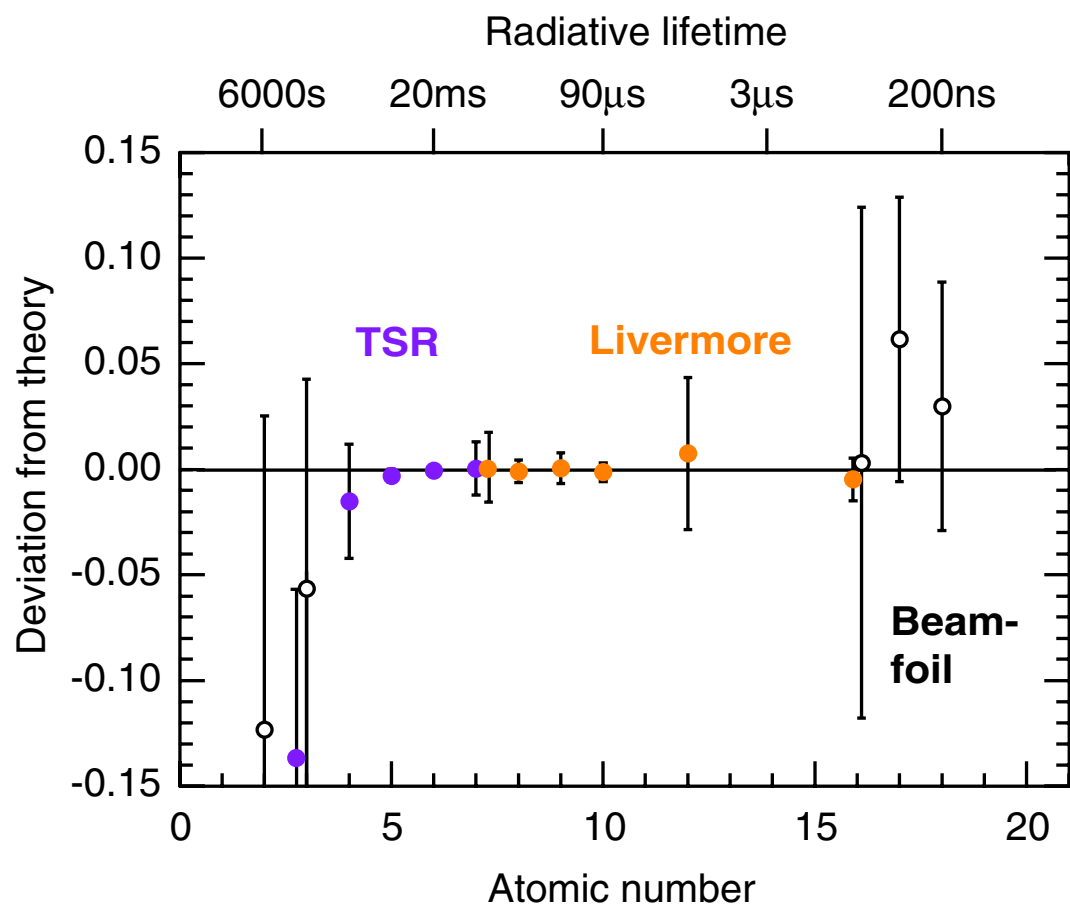


Figure 21: Fractional difference between the radiative lifetimes of the  $1s2s\ ^3S_1$  level in heliumlike ions measured at various facilities and theory.

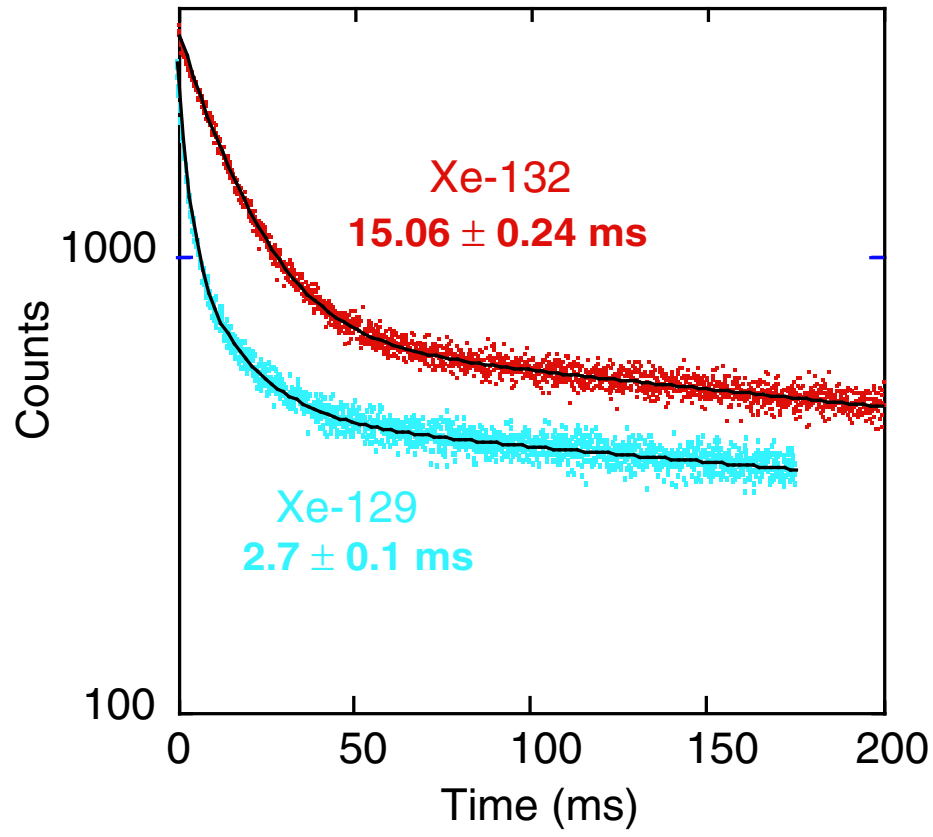


Figure 22: Measurements the radiative decay rates of the  $3d_{5/2}^9 4s_{1/2} ^3D_3$  level in two isotopes of nickellike  $\text{Xe}^{26+}$  performed at the SuperEBIT electron beam ion trap (adopted from [135]).